Biomechanics of cross-country skiing locomotion

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The candidate confirms that the work submitted is his/her own and the appropriate credit has been given where reference has been made to the work of others.

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Cross-country skiing constitutes ancestral method for moving along in a snow environment. A number of techniques have been developed to facilitate this. Among these techniques, one of them; namely the Diagonal Stride Technique (DST) has been described by authors as an extension of walking and running. Most biomechanical research studies have analysed the DST as a sporting activity leaving the locomotor strategies poorly described. This relationship to walking and running and the involvement of a gliding phase make the DST an interesting locomotion which may reflect a locomotor adaptation of human to the environment.
The overall purpose of the research undertaken in this work was to determine the strategies employed by skiers to progress along the ground in the DST.
Different analytical approaches were used to test the research question: those involved cycle patterns, joint angular kinematics, coordination and mechanical analyses of different skiing conditions. The DST with poles was tested for two different speeds. In addition, the DST was investigated without poles.
The description of the joints angular kinematics showed that specific movement patterns and segmental organisation were required for skiing with a reference to walking and running. The DST locomotion was mechanically similar to running but involved a gliding phase. The generation of forward displacement was carried out using an effective sequencing of hip extension and knee and ankle extension. Poles were reported to contribute to the generation of upper and lower body propulsion strategies. They were also supposed to increase the balance of the skier by providing additional supports. The increase of speed was achieved through faster limb movements without change in the joints range of motion.

The overall conclusion of this work is that although the DST could be related to running, the skiers developed some specific body segmental organisations to progress along the ground, in response to the properties of the environment and of the material.

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CHAPTER 1. GENERAL INTRODUCTION

Humans use different gaits for progressing along the ground (i.e. walking, running or skipping). Among them walking constitutes the most economical locomotion (Alexander, 1992a) requiring small muscle activation for propelling the body (Mochon and McMahon, 1980). Walking is mechanically limited to a speed of about 3 m/s (Alexander 1991a). To increase speed of transportation humans change its gait to running. However, running is also physiologically and mechanically bounded to 11m/s (Minetti, 2004).

In the attempt of increasing the speed of personal transportation humans have designed a wide variety of tools (e.g. bicycle, ice-skates or roller-skates), technologically evolved. These locomotions allowed a large increase of the speed (40 to 60 km/h) achieved by enhancing body motion by better exploiting muscles through a change of the segmental organisation or an increase of the duration of propulsion.

Cross-country skiing enters in this group of assisted locomotions that are practised with tools, namely skis and poles. It has been developed over thousands of years, as a locomotor answer to efficient movement over the snow environment. First people designed snow-shoes to counteract the softness of the ground. Then, they designed skis to exploit the gliding properties of the snow. In cross-country skiing the environment allows an increase of the speed of travel and indeed a decrease of the cost of locomotion (Saibene et al., 1989; Mognoni et al., 2001; Formenti et al., 2005).This contrasted with walking and running on soft ground (e.g. sand, snow) where it requires greater effort for transportation (Lejeune et al., 1998), cross-country skiing involves a unique range of techniques which beneficiates from the gliding properties of the skis on the snow. Although the Diagonal Stride Technique (DST) is the most ancestral and common technique encountered in cross-country skiing (Lind and Sanders, 1996), it is also interesting because involving sagittal movement of the limbs similar to walking and running (Street, 1990; Von Duvillard et al., 2000; Smith, 2003). This characteristic has led authors to describe the DST as an extension of walking or running (Street 1990; Smith, 2003).

Nowadays, DST is both a means of everyday transportation and a sporting activity. The recent development of cross-country skiing as a sport impacted on the research topics taken by sport scientists. Indeed, most of the biomechanical studies analysed in the DST the main factors responsible for high performance level (Norman et al., 1985; Norman and Komi, 1987; Bilodeau et al., 1992, 1996). The studies led to the comparison of the kinematic and mechanics of skiers with different expertise background (i.e. expert versus recreational skier). In contrast, little research has focused on the understanding of the general strategies developed in the DST to progress along the ground. The few kinematic and mechanical analyses of the DST were methodologically limited (Komi et al., 1982; Normal et al., 1989) disallowing an accurate representation of the skiing locomotion. Additional studies have mostly focused on the basic cycle kinematic (e.g. cycle velocity, cycle length frequency, glide duration or propulsion duration) (Gagnon, 1981; Roy and Barbeau, 1991; Nilsson et al., 2004) and the kinetic of the DST (Komi, 1985; Pierce et al., 1987) was mostly descriptive. Therefore, there is a limited understanding of the technique used by the skiers to efficiently progress on the snow.

The DST constitutes an original locomotion which involves a gliding phase and showed some qualitative similarities with terrestrial gaits. The analysis of the technique used in the DST represents also an attempt to investigate the adaptation of human locomotor patterns to a specific environment.

The overall purpose of the research program was to describe the biomechanical mechanisms used in the DST to progress along the ground. The general hypothesis being that skier produces an effective locomotor technique adapted to the environmental and material constraints. To do so, full body kinematics and body centre of mass mechanics were undertaken on the DST locomotion.

More specifically, this work aimed to:

- Describe the movement strategies that generate locomotor displacement in the DST.
- Determine the overall mechanics used in the DST to progress along the ground.
- Understand the role of the joints in the generation of the body centre of mass velocity.
- Understand the roles of poles in the progression along the ground.

- Develop an understanding of the techniques used for increasing speed in the DST

The thesis begins with a review of the literature on the biomechanics of the DST, and on the techniques used for the analysis of human locomotion. The literature review leads onto the formulation of the research question and the main research objectives (chapter 2). Preliminary studies and the description of the experimental methods are reported in chapter 3. The four main investigations undertaken are presented in chapter 4. The results of these four studies are brought together and discussed in chapter 5.

CHAPTER 2. LITERATURE REVIEW

2.1 Characteristics of the Diagonal stride technique locomotion in cross country skiing

2.1.1 Cross-country skiing: overview

2.1.1.1 History of cross-country skiing

Skiing has both a prehistory and a history. Norwegian pictographs as well as the archaeological recovery of ancient ski fragments suggest that some form of skiing was pursued as a mode of travel over snow from at least 4000 year ago (figure 2.1).

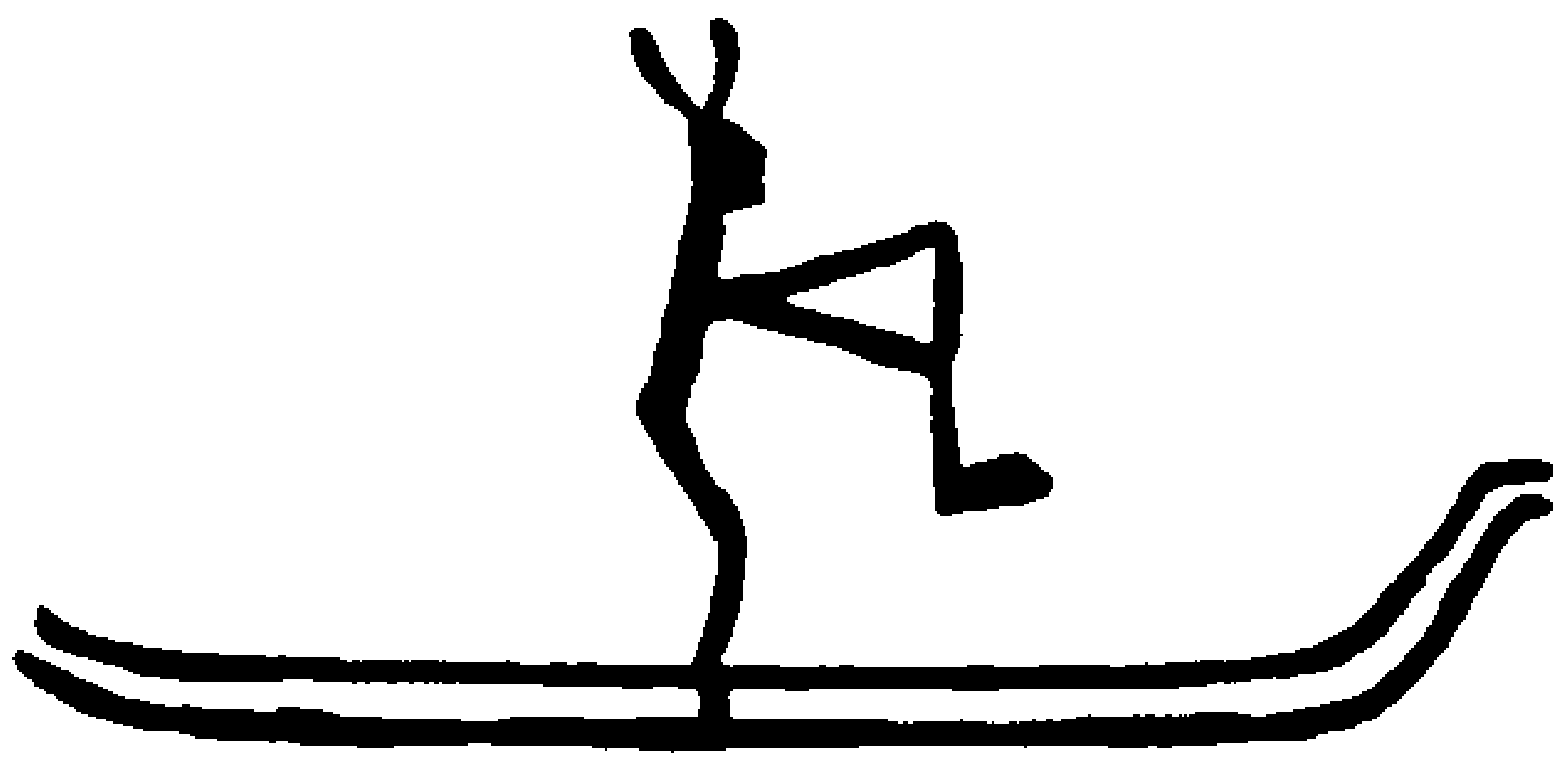


Figure 2.1: Pictograph from Rödöy, Norway, circa 2000 B.C. (from Lind and Sanders, 1996).

The first practitioners were probably the migratory Sami of what are now northern Norway, Sweden and Finland, living very near the Arctic Circle. The utilisation of skis as an adaptation to the harsh environment gave these people greater mobility for travelling through soft snow and hunting for reindeer. The very difficult environment, particularly during the long freezing winters, forced many Artic dwellers to adopt a nomadic lifestyle, maximizing the energy they could extract from prey and food in general, and minimizing energy wastage (Freuchen, 1935). The design of the skis allowed for a gliding gait, thereby increasing the speed of travel and reducing the cost of locomotion (Saibene et al., 1989; Mognoni et al., 2001; Formenti et al., 2005). From this perspective, the skis represented means of transportation which reduced migration time, increased hunting performance and optimised survival (Formenti et al., 2005). Therefore, in contrast to initial expectations that the winter season may make life more difficult, the arrival of the snow actually improved the day to day lives of the indigenous population. During the summer one can propose that making one's way in the forest and around the lakes was more time consuming and physically very demanding.

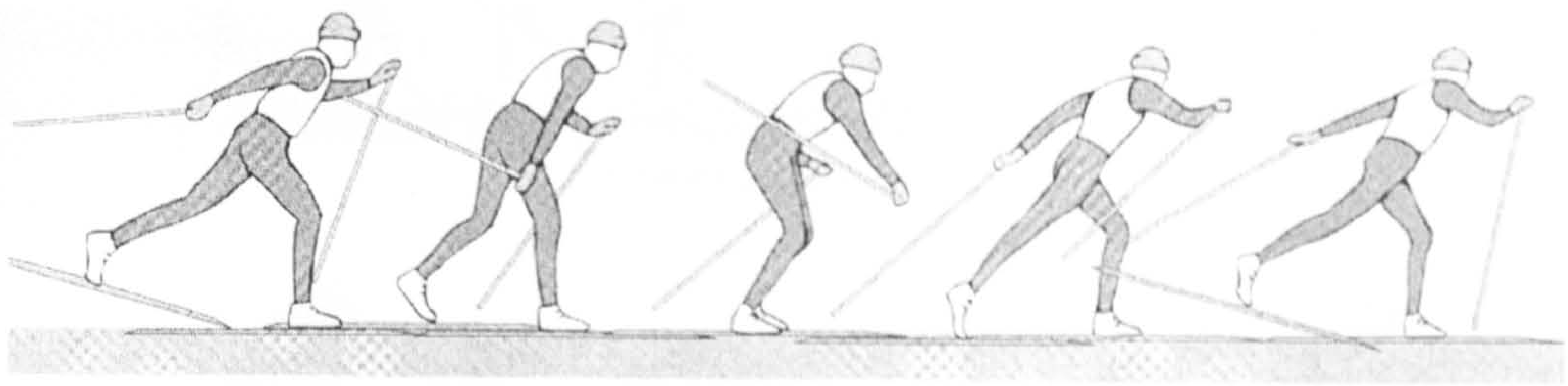
The use and knowledge of skis developed southward throughout Scandinavia. The improvement of ski design was related to a decrease of the metabolic cost of transportation (Formenti et al., 2005).

Until the 20th century, cross-country skiing was largely a means of general transportation utilized by northern Europeans. Nordic and German immigrants carried their knowledge of skiing to countries where snow was compromising the local way of life. For example, at the height of the American gold rush, mail carriers used skis to make their deliveries. During the last century, cross-country skiing progressively gained popularity through organised ski schools and developed as a sporting activity. The emergence of national and international competitions in Scandinavia in the 19th century popularised cross-country skiing in both European and America. The effect of this popularisation was to increase the number of practitioners and develop further skiing facilities.

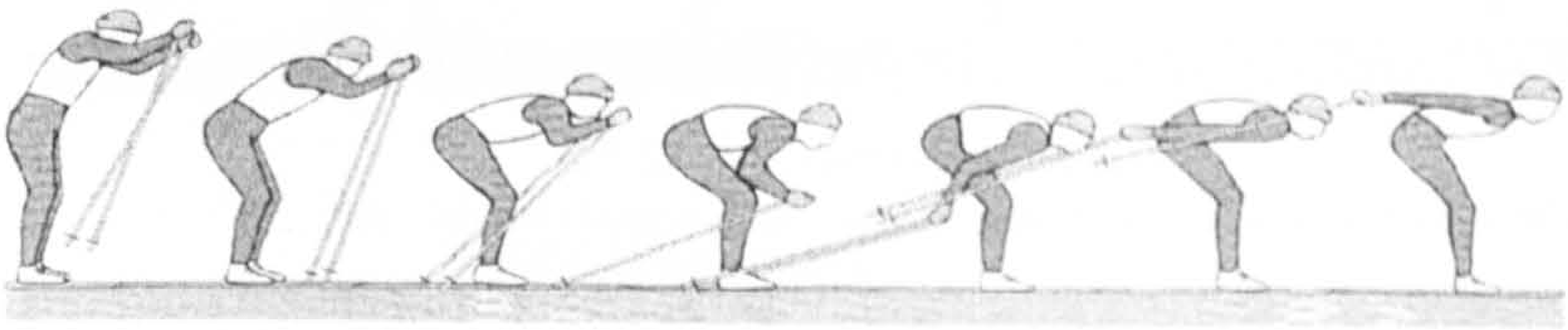
Today, the improvements in equipment have led to refinements of ski type. Mountaineering and back-country skiing involves a walking-like locomotion of skis and poles on untracked snow, whilst allowing for free glide on downhill terrain. With the use of lighter materials and groomed trails, highly skilled techniques have emerged. These techniques involve gliding under all terrain conditions thereby increasing the locomotor efficiency (Saibene et al., 1989; Bellizzi et al., 1998; Formenti et al., 2005). Two main cross-country skiing styles are used on groomed snow: the classical technique and the skating technique.

2.1.1.2 Classical techniques

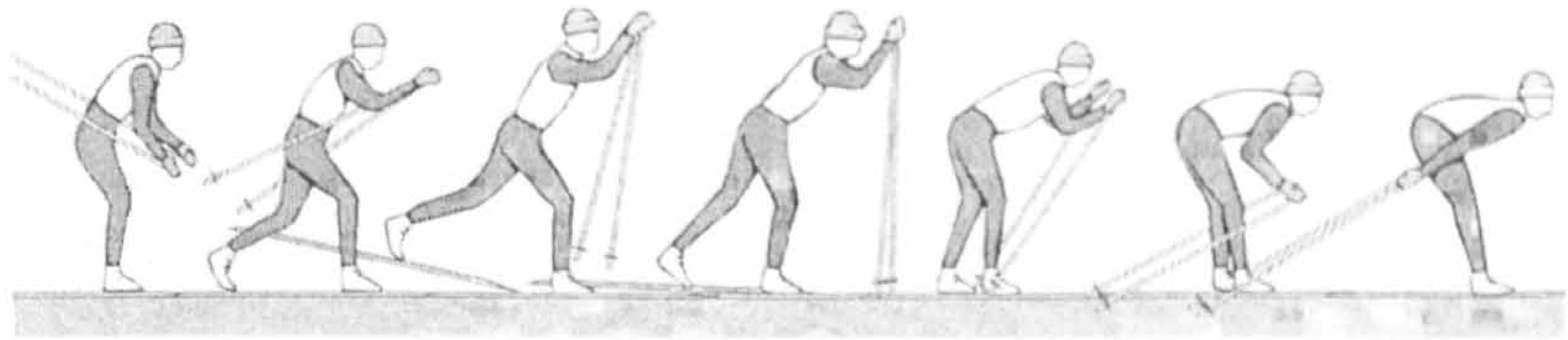
The classical style evolved from traditional methods of Nordic skiing. It is mainly represented by the Diagonal Stride Technique (DST) that is used to negotiate flat to uphill terrains by skiing in parallel tracks. The skiers propel themselves by moving their poles and skis in a diagonal relationship to each other: the right pole stretches ahead as the left ski slides forward, the left pole stretches ahead as the right ski slides forward, and so forth. As the skier encounters terrain and environmental conditions that affect the speed and metabolic demands of moving over snow, he uses various locomotion patterns such as double poling or the kick-double poling technique (figure 2.2).



Diagonal stride technique



Double poling



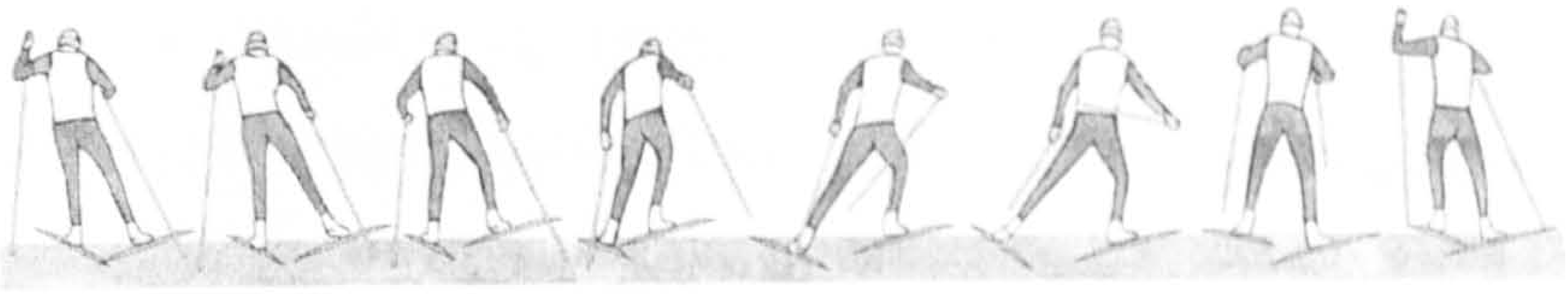
Kick double poling

Figure 2.2: Techniques of the classical style of cross-country skiing (adapted from Smith, 2003).

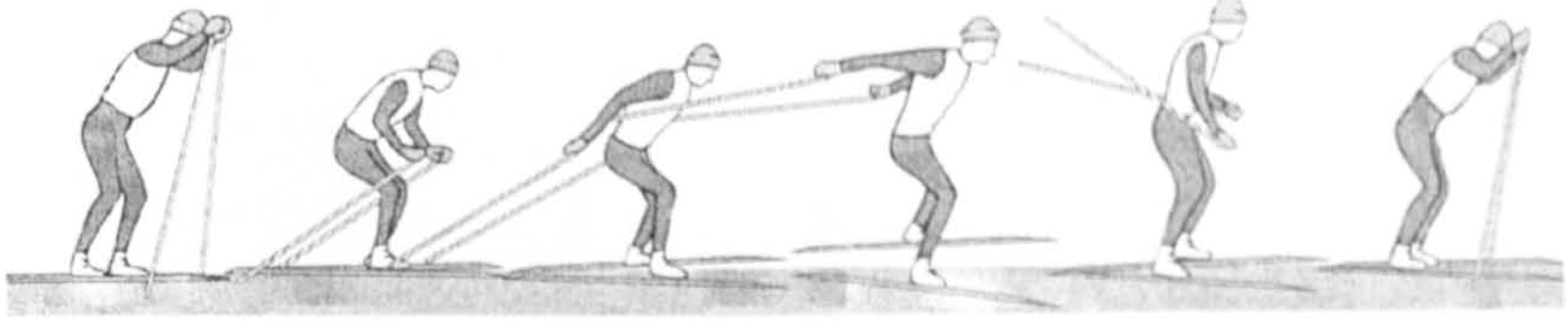
2.1.1.3 Skating techniques

The skating style appeared in the late 1980's. The technique involves an ice skating motion with substantial use of the upper body for propulsion. The skating style is composed of three techniques commonly denominated "V1 skating technique", "V1 open field skating technique" and "V2 skating technique" (figure 2.3). They are mainly characterised by the different coordinations existing between the upper and the lower body. Both "V1" and "V1 open field" skating techniques are defined by the use of a poling propulsion every two leg supports. The timing of the application of pole forces within the cycle differentiates them. "V2" skating technique shows a poling propulsion for each leg support (figure 2.3).

Practically, V1 is mostly used over predominantly uphill terrain, whereas V1 open field and V2 are primarily used over flat terrain.

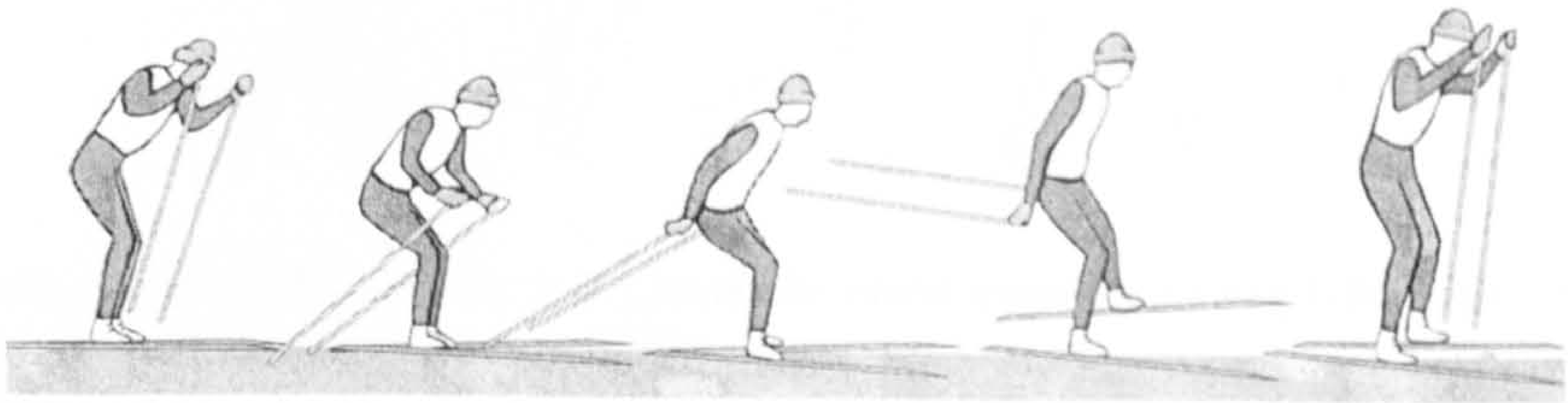


V1 Skating technique



V1 Skating technique - open field

⇒ Arm propulsion every two leg support (on the figure arm propulsion for each right leg support)



V2 Skating technique

⇒ Arm propulsion for each leg support

Figure 2.3: Skating techniques of cross-country skiing (adapted from Smith, 2003). The three techniques (V1, V1 open field and V2) differ mostly because of varying inter-limb coordination.

2.1.2 Movement Description of the Diagonal Stride Technique

In contrast to the skating technique, which appeared as a novel form of human locomotion, the actual DST, as executed by highly skilled skiers, represents the latest evolution of an ancestral locomotion. The DST is essentially a cyclic activity involving fundamentally opposite movement patterns of the arms and legs (Smith, 2003) (figure 2.2).

Limb movements are highly constrained in the sagittal plane because of the parallel tracks, with arm and leg propulsion forces directed both backward and downward (Komi, 1987). Dal Monte et al. (1983) reported that, from the observation of the skier's movement, the existence in the DST of some characteristic elements of running was probable. Parks (1986) and Smith (1990) reported that the rhythmic movement of the upper and lower body extremities used in the technique was much like those of walking and running. Therefore, some authors proposed the diagonal stride technique to be an extension of walking (Street, 1990), or an adaptation of walking and running to a specific environment (Minetti et al., 2001a). Furthermore, beginners in the DST adopt a very erect position of the trunk and flex knee while returning the leg forward (figure 2.4). These characteristics are common with walking patterns (Mann and Hagy, 1980; Perry 1992).

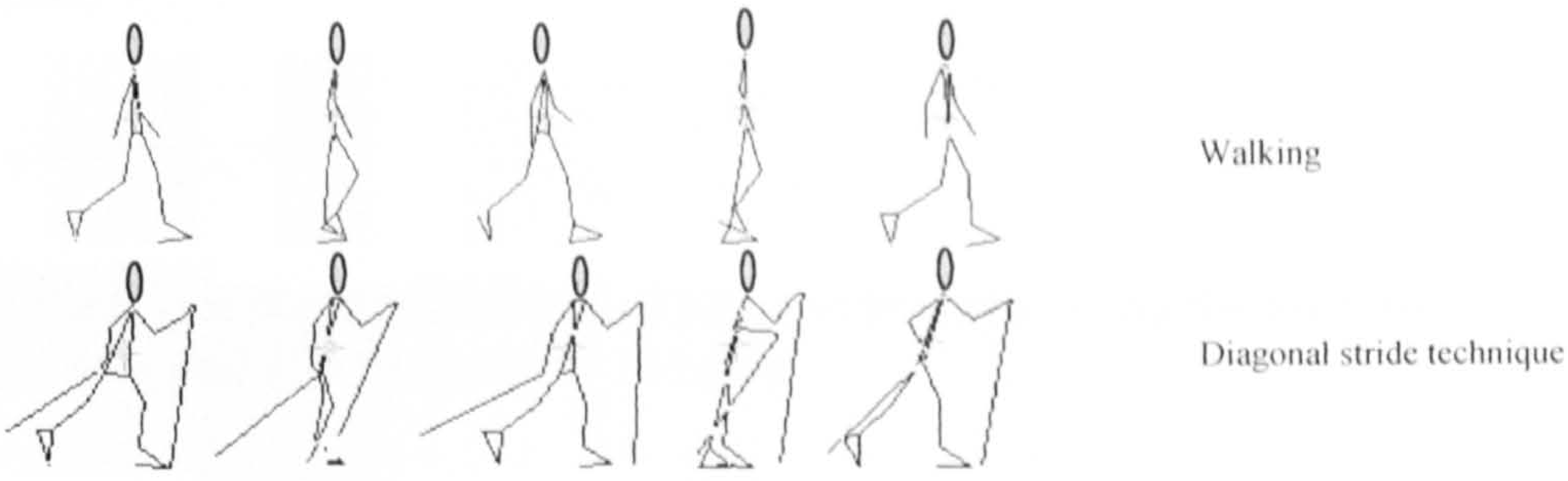


Figure 2.4: Walking and DST gaits for a beginner in cross-country skiing (illustration made from Ski nordique enseignement et technique, 1999)

Although the limb movements appear to be similar to walking or running, the environment in which skiing is practised differs dramatically. In walking or running, the environment is stable, with a non-slippery configuration of the ground. Furthermore, walking and running are naturally practised without external materials. In contrast, the DST is practised in a rather challenging environment involving a gliding motion over snow. The utilisation of skis and poles also enhances the locomotion (Saibene and Minetti, 2003).

Consequently, the movement of the DST cannot be evaluated in isolation from the environmental factors. The environmental and material characteristics of the DST must be considered in the analysis of the locomotion

2.1.3 Environmental characteristics of the DST

Unlike walking and running in which the forces opposing motion are mainly gravitational and forces of inertia, in the DST the environment generates additional mechanical constraints namely those generated by the friction between the skis and snow (figure 2.5).

The major force acting on the skier is, however, gravity that is determined by the skier's mass and is always directed vertically downward. Travelling downhill, a proportion of the gravitational force of the skier is directed forwards and acts to propel a skier down the slope. In a similar manner travelling uphill, gravity acts against the skier's motion.

Secondly, air resistance or drag air is a complicated force which depends on a skier's shape and size, on the atmospheric pressure and temperature, and on the relative air velocity (Walter, 1994; Kreighbaum and Barthels, 1996). The drag force can be calculated using equation 2.1.

Equation 2.1: $F_D = \frac{1}{2}(\rho \times A \times C_D \times V^2)$

Where F_D is the drag force, ρ is the mass density of air, A is the area facing the air flow, C_D is the coefficient of drag and V is the relative velocity.

The origins of air drag force are ultimately caused by pressure differences on the front and back of a skier's body.

A head wind will cause air drag forces to resist a skier's forward motion while a tail wind blowing faster than a skier's forward motion will help propel that motion. Hence air drag, like gravity, can be propulsive or resistive in direction. More specifically to the DST, the snow drag force is always acting against the skier's forward motion (Frederick, 1992).

Numerous factors, such as snow conditions, wax and ski stiffness influence the magnitude of snow drag and thus the ability of gliding on the snow (Colbeck, 1995). The snow drag force is directly related to the coefficient of friction existing between the ski and the snow as reported in equation 2.2:

Equation 2.2: $F_f = \mu \times F_N$,

where F_f is the friction force, μ is the coefficient of friction and F_N the gravitational force.

Whilst F_N is a constant, μ dramatically affects the magnitude of snow drag. A large coefficient of friction will result in larger drag force. A low coefficient of friction such as that reported for compact snow (e.g. around 0.05) will induce lower snow friction force. The coefficient of friction μ represents a quantification of the physical interactions between the snow and the ski sole. These interactions highly depend on the physical parameters of the snow such as: the solid or liquid water phase, the snow temperature, the compactness of the snow surface and the snow contaminants. In addition, the ski preparation, the ski waxes and the ski surface roughness can also affect the coefficient of friction value (Smith, 2003).

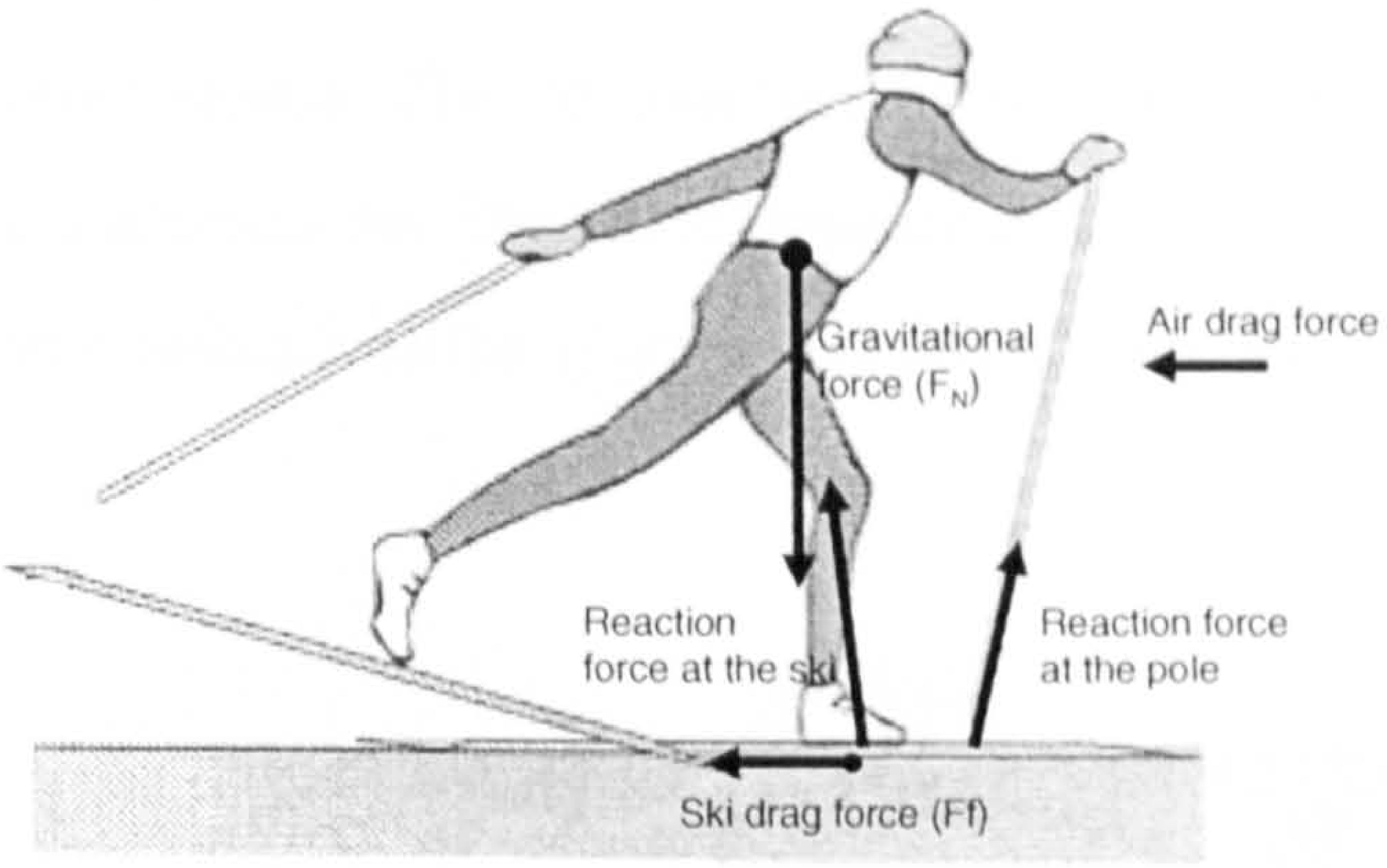


Figure 2.5: Forces acting on the skier in the DST (adapted from Smith, 2003).

The basic phenomenon of the ski and snow friction generates a melt water lubrication above the ground that helps skis to slide over the snow.

A very low melt lubrication (mainly dry friction between the ski and the snow) or a very large melt water lubrication (mainly viscous friction between the ski and the snow) will reduce the quality of gliding. Therefore, the “art” of the skier will be to obtain from the environmental conditions the best gliding ability (Lind and Sanders, 1996). Whilst there is little that a skier can do to change the effect of gravitational force in slowing or propelling him down the tracks, air and snow frictional forces can be affected by skier technique and equipment (Frederick, 1992; Smith, 2000, 2003).

2.1.4 Materials used in the Diagonal Stride Technique

2.1.4.1 Skis

The DST movement performance is highly dependent on the quality of the equipment used (Millet, 1999; Smith, 2003). A wide range of DST skis is available on the market. They are specifically designed to fit the different uses (from off-piste to track DST) and the levels of expertise of the skiers.

Good skilled skiers preferentially use cross-country skis that are manufactured from light and modern materials (e.g. carbon fibre). More specifically, the DST ski is around 2 meters long, depending on the height of the skier, and quite narrow with mean side cut dimensions of 42 mm.

It is relatively light (500 grams) compared to that of beginner and back country skis, minimising the leg return inertia. The ski structure is built up so that it facilitates the generation of glide and propulsion. The ski's pressure distribution under load is an important feature which influences the gliding and propulsion quality in skiing (Smith, 2000).

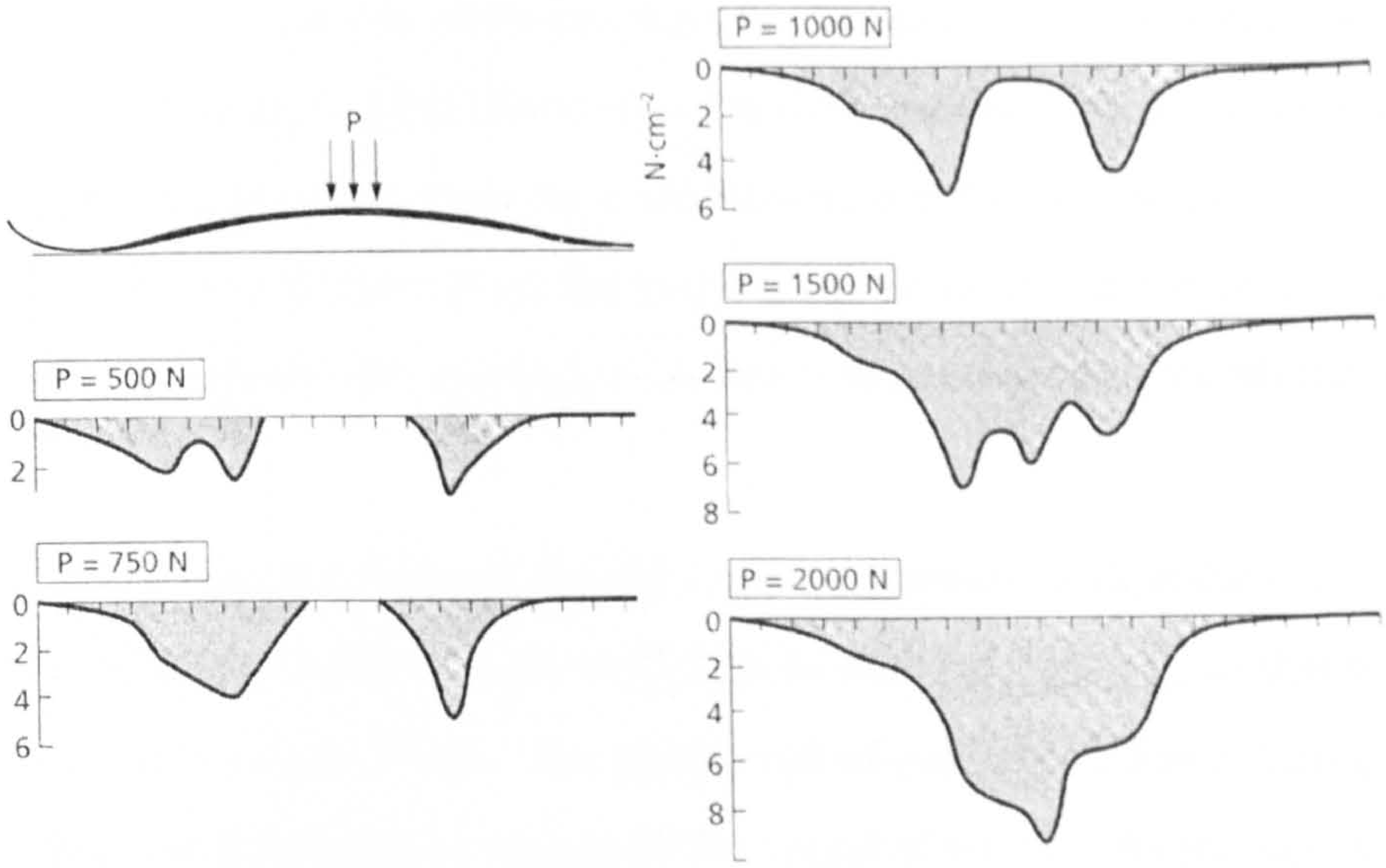


Figure 2.6: Pressure distribution pattern under a ski depends on the applied force. Under a classical ski, a region of low pressure exists in the middle for moderate vertical forces (under 75 % of body weight). However, with greater loading (larger than 75% BW) the mid-region of the ski experiences pressure allowing the grip wax to grip on the snow (From Ekström, 1981).

Skis must support the skier's body weight so that the ski tip does not plough through the snow whilst the mid-section of the ski should not drag. A ski designed to optimize glide will distribute the skier-applied forces in a smooth pattern without local fluctuations. The local fluctuations are thought to increase drag. The style of skiing (i.e. classical or skating) is taken into consideration in the design of the skis. Classical skis are designed primarily to glide in tracks. They must be capable to show different pressure distributions under varying loads. A classical ski must be able to flex sufficiently to press the ski mid-section firmly against the snow (for the wax to grip) but also to glide smoothly on the tip and tail regions when moderately loaded (figure 2.6). Grip on the snow is made through the application of a grip wax under the central part of the ski, which is dependent on the condition of the snow (Smith 2000). Gliding, however can be passively obtained from the use of the skis, the propulsion from the legs must be obtained from active pressure of the skier on the mid-section of the skis.

As in walking and running, the propulsion forces in DST are generated when the foot comes to a stop. The properties of the skis allow the skiers to progress along the ground using an alternating gliding-griping on the snow.

2.1.4.1.1 The alternating gliding-griping

Whereas skis allow gliding, skiers still have to generate propulsion for maintaining their speed. One can observe timing when the skier is gliding and timing when the skier is propelling. This principal original feature of the DST locomotion is owing to the properties of the skis (i.e ski's pressure distribution) and the utilisation of the kick wax. The basic phenomenon that produces the grip-and glide bond must involve the embedding of snow grains into the kick wax that was applied underneath the mid-section of the ski.

As long as the skier applies force to the ski so that it presses against the snow, the strengths of both ice and kick wax are sufficient to prevent slipping, so that traction is possible (Lind and Sanders, 1996). The generation of propulsive force during the propulsion phase requires careful timing of the speed of the ski. As the ski slows to a stop, the skier must quickly compress the cambered mid-section of the ski to the snow surface which momentarily creates a static frictional force (Smith, 2003).

This alternating gliding –griping can be observed through the characteristic horizontal and vertical forces patterns. In the DST, vertical forces are firstly applied in order to allow adherence between the skis and the snow. Vertical ski reaction forces were reported to be important and have been measured to be up to 2.5 times of the body weight (Ekström, 1981; Pierce et al., 1987; Komi, 1985, 1987) (figure 2.7). When sufficient grip on the snow is available (i.e. maximum vertical ski force) the horizontal component of the ski reaction force gets larger (figure 2.7). The backward directed forces reach a peak of horizontal force of 25 % of body weight that produce the forward displacement of the skier. In order not to compromise the whole body velocity, the initial vertical leg force must be applied in a short period of time, estimated to be less than 300 ms (Ekström, 1981; Pierce et al., 1987; Hoffman and Clifford, 1992).

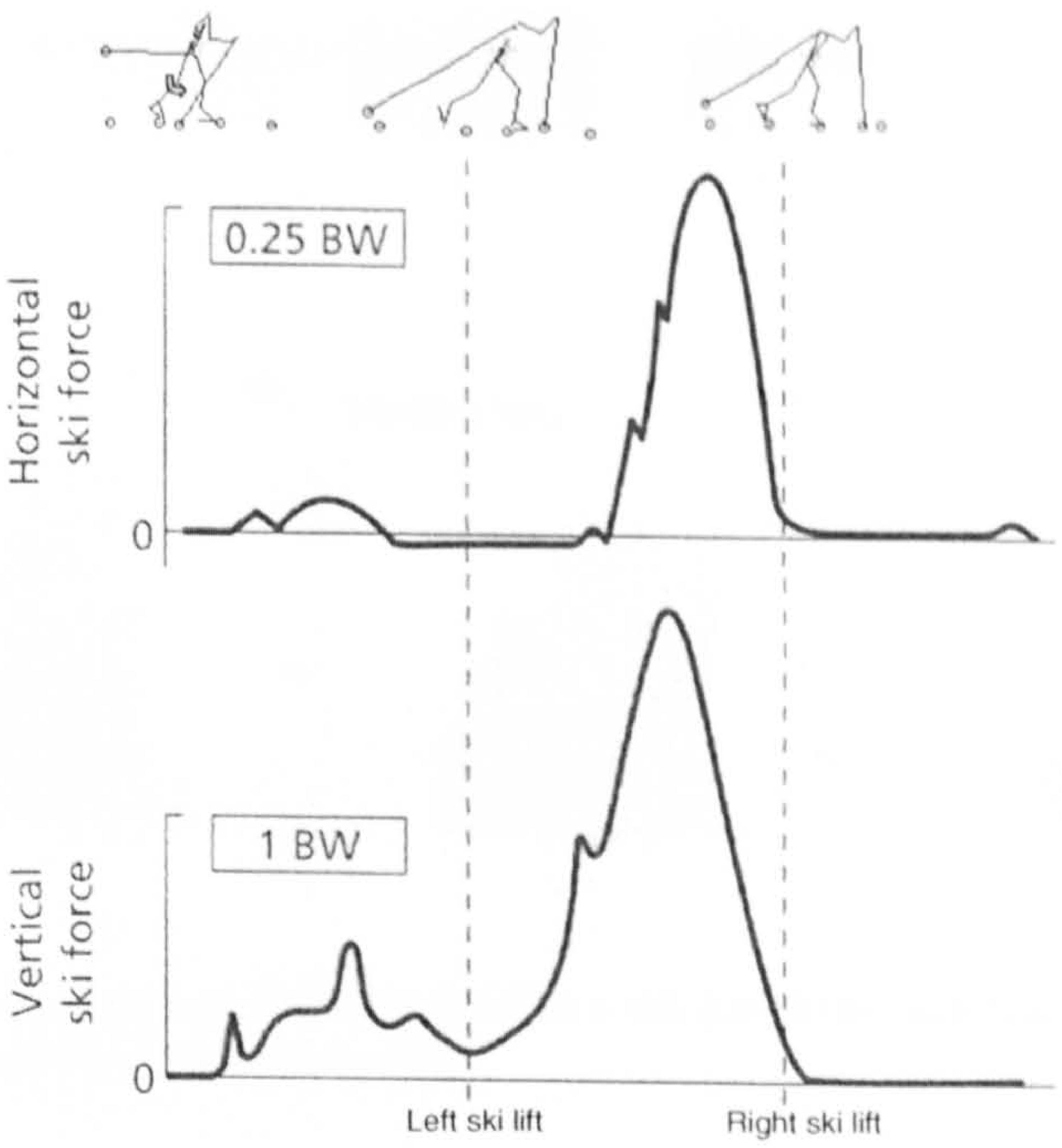


Figure 2.7: Typical ski reaction force observed during the DST, expressed as a ratio of body weight (BW) (Adapted from Komi, 1985).

The strength of the linkage between the ski and the snow may depend on the choice of the adequate skis for the skier's weight and appropriate wax to the snow. In addition, the generation of propulsive force becomes more difficult as the slope becomes steeper. The generation of ski force perpendicular to the surface affects the horizontal frictional force, thus, the grip during propulsion phase.

2.1.4.1.2 Ski and wax grip effects

In addition to the environmental conditions, the materials (i.e. skis, kick wax and poles) may be influencing the force and movement patterns of the DST.

Very little data have been published on the effect of the quality of the skis (i.e. pressure distribution, length) over the propulsion and general kinematic patterns. This kind of analysis is difficult because it can be dependent on a large number of factors. Ski manufacturers may have proprietary information detailing such relationships but little is available in the scientific literature.

A few data are available on the grip wax effect on the ski reaction forces. Komi (1987) reported the vector direction of the leg propulsion forces under 3 different grip wax conditions, poor, medium and good (figure 2.8). Whereas we observed an increase of the horizontal ski reaction force with the quality of the grip wax, no further information has been elaborated into text.

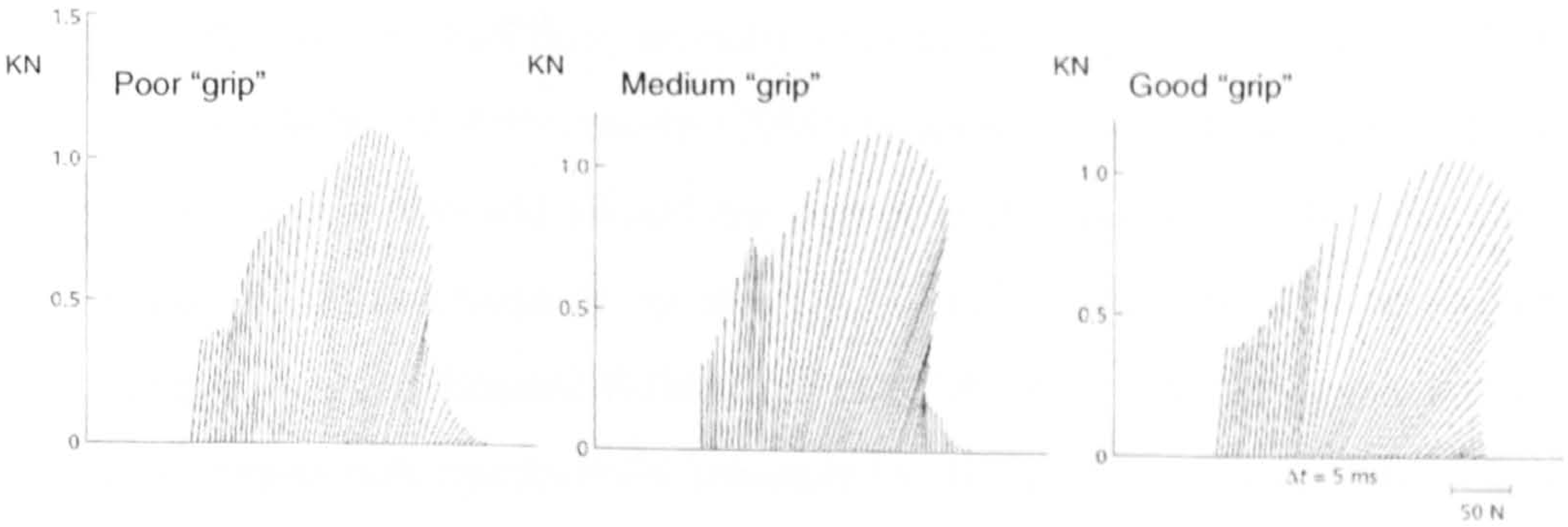


Figure 2.8: Direction of the reaction force applied to a ski for three kick wax conditions: poor, medium and good (adapted from Komi, 1987).

2.1.4.2 Poles

The DST is practised with poles which allow upper body propulsion (Komi, 1985; Pierce et al., 1987). The contribution of the poles for propelling the body is getting larger in uphill condition (Komi, 1987). Skilled skiers use poles specifically designed for racing which are manufactured using very light and rigid materials (e.g. carbon, Kevlar). This allows the pole's centre of mass to be situated closer from the handle. In addition the moment of inertia of the poles when rotating around the wrist is reduced, decreasing the workload on the joint and making the poles easier to use. For the DST, the pole dimensions depend on the standing height of the skier. Most commonly the length of the pole is measured as the distance between the ground and the mid-point in the skier's shoulder.

2.1.4.2.1 Ski pole length and grip

The pole length has been for many years an issue for coaches and practitioners (Siletta, 1987). Since low arm propulsion forces are generated in the DST (Komi, 1985; Bellizzi et al., 1998), the effect of pole on the skiing speed has been essentially documented for the skating technique (Hilden et al., 1993; Millet et al., 1998a, b; Street and Frederick, 1995) and / or double pole techniques (Holmberg et al., 2005) where the upper body can generate forces, up to 2 body weights. The studies were undertaken for determining the most efficient pole length. Siletta, (1987) reported that skiers with the longest poles (i.e. an increase of 10 % of the normal pole length) were faster using an uphill skating technique. However, this result was not elaborated upon with a biomechanical analysis of the skier's upper body with longer poles. An important characteristic of the poles deals with its mass and mass distribution within the pole. Street and Tsui (1987) reported that adding a basket to the shaft may increase overall mass by 15% or more and increase the moment of inertia by 32-49%. Smith (2000) proposed that with longer ski poles, the mass and the inertia increase and affects the energy cost and perhaps the kinematics of poling. Furthermore, the increase of the moment of inertia will tend to increase the time required to swing the pole forward during recovery, directly decreasing cycle rate. On the other hand, longer poles potentially increase the poling time, during which greater propulsive impulse may be generated.

Researchers have also turned their attention to the ski pole grip as having a possible impact on the pole forward propulsion. Using the double poling technique, Street (1990) and Heil et al. (2004) showed a difference in the maximum upper body propulsion forces generated with different grip systems. A modern grip system, with a strap that goes around the wrist, was reported to generate higher upper body propulsion under uphill or sprinting conditions. The authors proposed that the grip system may alter or increase the range of motion during which forces are applied through the ski poles.

More generally, the quality of the pole may influence the skier's kinematic and kinetic pole propulsion. For example, a heavy pole can increase the pole moment of inertia and create a strong disadvantage for the skier. Furthermore, the stiffness of the pole may influence the transfer of the upper body forces to the ground. Very few published data are yet available on these questions.

2.1.4.2.2 Effect of poles in DST

In DST, as in walking and running the action of the arms seem to be opposite and synchronous with the action of the legs. In walking, it has often been suggested that the arm helps to keep the trunk facing straight ahead, not turning too much to the left and the right in each stride. The arm movements would help to counteract the effects of the leg movements. Although this hypothesis has been dismissed with the comparison of normal walking with walking without the swinging of the arms (Alexander, 1992a) in DST, it remains a strong hypothesis since the arms are actually producing forces on the ground via poles and torques about the vertical axis. Hence it may be assumed that the opposite application of propulsion forces from the ski and poles acted such as no net torque may be generated about a vertical axis (figure 2.9).

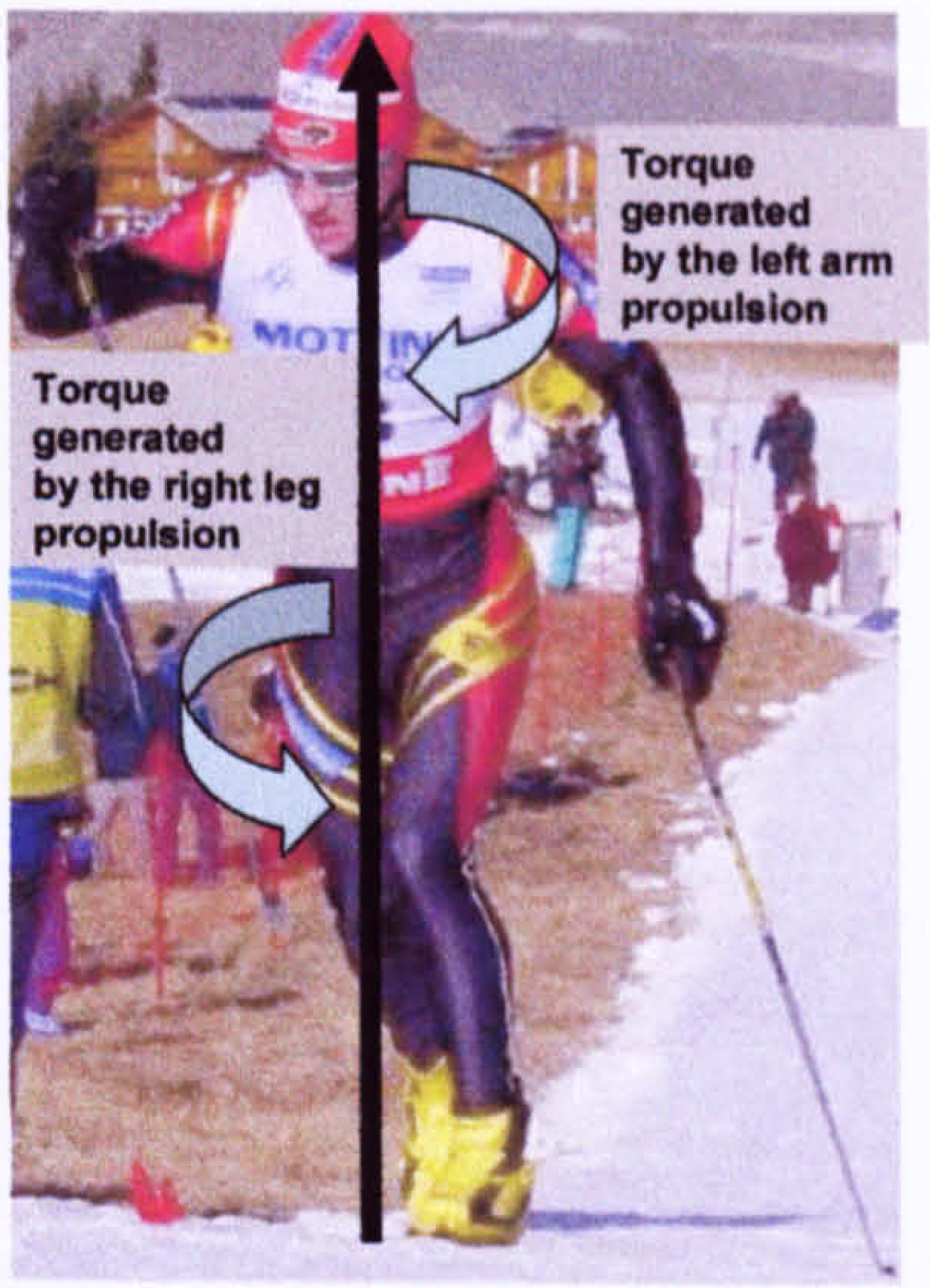


Figure 2.9: Torques generated by leg and arm propulsion about the vertical axis. As the two torques cancel each others no net torque is generated (adapted from Smith 2003).

To summarise, one can report that skiers used skis and poles to 1) apply forces on the ground to propel themselves along the ground and 2) glide on the snow to use the environmental properties. One way of reporting the advantage of gliding in DST may be observed by comparing cycle length, speed and energy cost of locomotion between DST and walking and running.

2.1.5 Impact of gliding on the DST

2.1.5.1 Cycle characteristics of the DST

A simple way to account for the effect of gliding on the locomotion has been to present the cycle length, cycle frequency and cycle velocity previously reported in the DST literature with reference to walking and running data. In addition, results from different terrain conditions have been presented with the idea that less gliding would be allowed in uphill section (Smith, 2003).

On flat terrain, depending on the skiing speed, the cycle length reported evolves from 5 m to 6.1 m whereas the cycle frequency ranges from 0.6 to 1 Hz. On flat terrain, the diagonal stride technique showed larger cycle length compared to running for similar speed and terrain conditions. Similarly, the range of cycle frequency values observed on flat terrain is much lower compared to walking and running (table 2.1).

Table 2.1: Standard cycle velocity, cycle length and cycle rate observed in the DST, in walking and in running for flat and uphill terrains.

	Testing Condition	Cycle velocity ($m \cdot s^{-1}$)	Cycle length (m)	Cycle frequency (s^{-1})	Authors
DST-Flat					
	15 km	4.70-4.92	5.38-5.92	0.81-0.87	Komi et al. (1982) Norman and Komi (1987) Norman et al., (1985)
	3 km	4.22	-	-	Bilodeau et al. (1991)
Selected speeds	Slow speed	3.1 to 4.47	5.08 to 7.90	0.57 to 0.70	Gagnon (1981) Nilsson et al. (2004) Roy and Barbeau (1991)
	Medium speed	3.8 to 5.38	5.7 to 7.14	0.70 to 0.75	Gagnon (1981) Nilsson et al. (2004)
	Fast speed	4.75 to 5	5.95 to 6.1	0.80 to 0.81	Bilodeau et al. (1992) Nilsson et al. (2004) Roy and Barbeau (1991)
	Maximum speed	5.64 to 6.79	5.9 to 7.90	0.90 to 1	Gagnon (1981) Karvonen et al. (1989) Nilsson et al. (2004)
DST–Uphill					
Race speeds	50 km (7°)	3.5	3.7	0.96	Bilodeau et al. (1996)
	30 km (12°)	2.58	2.36	1.09	Norman et al. (1989)
	15km (9°)	3.9	3.03	1.29	Norman and Komi (1987)
	Sprint (5°)	4.8	2.2	2.2	Zory et al. (2005)
Walking–Flat					
	From slow to fast speed	1.45 to 2.5	1.5 to 2	0.92 to 1.3	Murray (1967) Hay (2002)
Walking– uphill					
	Medium speed (9°)	1.15 to 1.4	1.28 to 1.5	0.9 to 0.95	Wall et al. (1981) Sun et al. (1996) Kang et al. (2002)
Running-Flat					
	Overall paces	2 to 9.2	1.4 to 4.6	1.35 to 2.6	Luthanen and Komi (1978) Williams (1985)
Running-Uphill					
	Medium speed (9°)	2.5 to 3.8	1.7 to 2.5	1.35 to 1.46	Takano (1995)
	Sprint running (3°)	7.8	4	1.95	Paradisis et al (2001)

These differences resulted from the gliding ability involved in cross-country skiing (Saibene et al., 1989). During the gliding phase, skis allow the foot to slide over the ground. As a result, skiers can glide forward while supporting themselves passively on a relatively straight leg (Bellizzi et al., 1998). The comparison of uphill terrain with flat DST showed that velocity and cycle length decreased while cycle rate increased (Dufek and Bates, 1987; Norman and Komi, 1987; Bilodeau et al., 1992; Smith, 2003). Under uphill skiing conditions, while the possibility for gliding is restrained (Bilodeau et al., 1992; Dufek and Bates, 1987; Smith, 2003), the DST cycle frequency did not differ as much as uphill walking and running cycle frequencies (Wall et al., 1981; Takano, 1995). Similarly, the uphill DST presents comparable cycle length values to uphill running (Takano, 1995). Therefore in comparison to walking and running, glide greatly influences the general cycle parameters of the DST: it reduces the cycle frequency and increases the cycle length.

Previous studies reported the relationship existing between the cycle frequency and the cycle length parameters, the mechanical and metabolic and cost of locomotion (Minetti and Saibene, 1992; Minetti et al., 1995). The calculation of the energy cost of locomotion in the DST can be an additional way of understanding the effect of the gliding phase on locomotion.

2.1.5.2 Energy cost of locomotion in the DST

The energy cost of locomotion gives some interesting insights on the economy of locomotion and of the related effects of the environment.

Comparisons between cross-country skiing and running revealed that although the metabolic power available to skiers and runners is virtually the same, the energetic cost of skiing is considerably lower (Saibene et al., 1989; Bellizzi et al., 1998; Mognoni et al., 2001). This difference between locomotions is the result of skier's ability to glide, therefore increasing the cycle length and reducing the cycle frequency (by half) in comparison to running. This means that changes of kinetic and potential energy are less frequent and external work minimised (Mognoni et al., 2001). More precisely, during the gliding phase period the skier effectively stands at rest while progressing forward. The forces required for supporting the body weight are generated for a minimal metabolic cost. Moreover, the cost of skiing can be reduced further by providing propulsive forces with the arms. Skis lower the cost of supporting the body against gravity and poles economize propulsion (Bellizzi et al., 1998). Therefore, skilled skiers use the environment and the material in order to reduce the cost of locomotion. The assessment of the cost of walking and running is a common, repeatable procedure that can be carried out in the laboratory under controlled conditions. However the cost of skiing must be measured in field experiments and is highly dependent on the environmental conditions. Since the external conditions can be different from one study to another, most of the variability in energy data in the literature resulted from the snow and the ambient temperature (figure 2.10). The friction of the snow (viscous or dry) has been found to be an important impact on the skiing speed and the oxygen consumption, hence on the cost of the DST locomotion (Saibene et al., 1989).

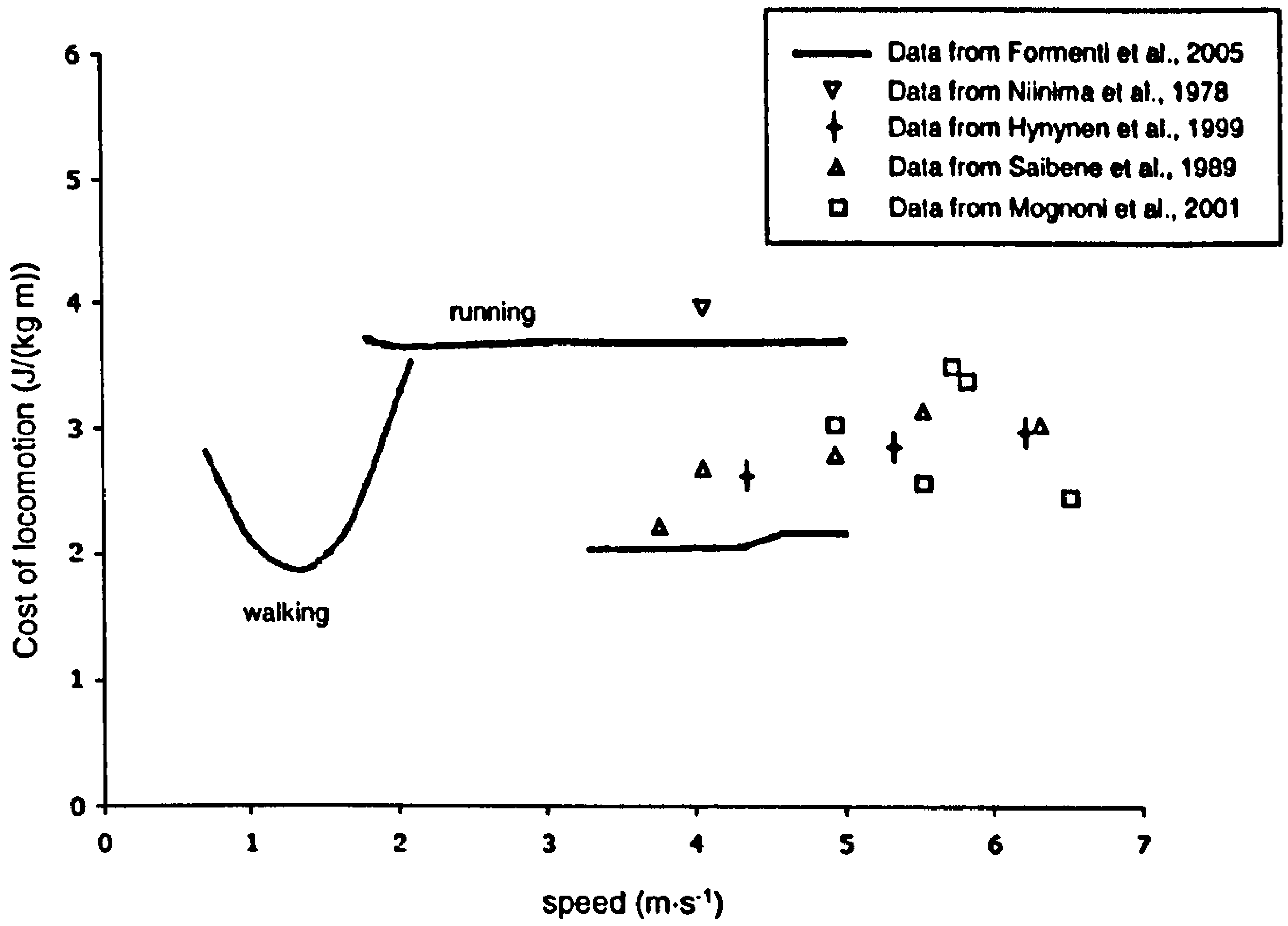


Figure 2.10: Cost of locomotion reported in walking, running and in the DST (adapted from Formenti et al., 2005).

2.1.6 Summary

In this section, the DST has been presented as an original form of locomotion developing from the demands of the specific environment and of the tools used. Although, it is mainly characterised by a gliding phase and specific leg and arm propulsions the DST showed similarities in the movement with walking and running. The glide enhances the DST making the cycle length longer and the locomotion more economical (table 2.1). The production of leg and propulsion forces is constrained by the properties of the skis and poles. All these characteristics suppose a specific adaptation of the skier's movement to manage all the constraints. Several types of equipments (i.e. accelerometers, gionometers, force platform, video cameras) have been used to analysis human movement. The following section will present the different techniques available for the study of sporting activities, outlining their advantage and inconvenient.

2.2 Tools and Measurement techniques for studying human movement

Several measurement techniques have been developed for recording human movement (i.e. force platform, electrogoniometry, isokinetic dynamometry, accelerometers and video based systems) each measuring different variables related to the movement. For example, force platforms are used to measure the contact forces between a person and the surroundings, electromyography is a technique used to record changes in the electrical potential of a muscle and isokinetic dynamometry is the assessment of the dynamic function of a joint during movement at a controlled velocity. Video data are extremely useful for coaching and movement diagnostics as much information can be obtained by intelligent observation and for qualitative and quantitative analyses.

2.2.1 Kinetic analysis

Newton's second law ($\sum F = m \cdot a$) linked the cause of motion (i.e. forces, F) with the effect generated (i.e. acceleration, a). The analysis of human movement may be done by investigating the causes of movement (kinetic analysis) or/and describing the movement (Kinematic analysis). The force platform has been the main piece of equipment used to analysis the force developed in human locomotion. These are used to record the contact forces between a person's foot and the surroundings. Force-time data, particularly when combined with joint position (kinematics) can be used to evaluate the effectiveness of a wide range of movement patterns in sport and exercise. Force platform is usually bolted to the ground and is therefore mainly laboratory based (Robertson et al., 2004). Force transducers can be used for measuring the force in equipment such as poles and skis (Komi, 1985; Pierce et al. 1987; Stoggl and Linderger, 2006). The difficulty of undertaking kinetic study in DST is important. It required either the application of force transducers between the ski and the foot or the positioning of force platform under the snow. Komi (1985) studied the kinetic of the DST, using force platform under the snow and forces transducers under the binding. However most of the data presented were not elaborated into text so no conclusions have been drawn with regard to skiing speed or level of expertise. Although kinetics analyses are important for explaining the causes of motion in any locomotion, the constraints of the environment in DST make the experimental set up difficult and costly.

In contrast, kinematic analysis can require little equipment, providing a description of the motion and to some extend through mechanical analysis, an explanation of the movement.

2.2.2 Kinematics analysis

Kinematics constitutes the starting point for a number of other analyses that can give considerable insights into both the biological and mechanical aspects of locomotion (Milliron and Cavanagh, 1990). Video-based systems constitute the main entrance to kinematic analysis because they allow a description of the way parts of the body move is space. Two main video based systems can be used for kinematic analysis. Both of them aimed to extract quantitative data from the body in movement in the form of joint coordinates. The first video system used simple video cameras but required the intervention of the experimenter for the selection of the joints location (i.e. digitising process). From these have been developed video systems that constituted the so-called automated or semi-automated motion analysis system. In this case the joint location is done automatically with little intervention by the experimenter.

2.2.2.1 Video cameras

From the video based system available today, the most convenient and least expensive system is the digital video camera (DV camcorder) that record at 25 frames per second (30 Hz for American and other standard video cameras). Each frame being composed of two separate, interlaced fields. Video sampling allows viewing of each separate field thus double the effective sampling rate to 50 Hz (60 Hz for American and other standard video cameras). The sampling rate is therefore limited to 50 Hz. However this does reduce the special resolution of the images generated.

The cameras used are by preference electronically shuttered (i.e. a device of a camera that controls the duration of a photographic exposure, as by opening and closing to allow light coming through the lens) to obtain a good unblurred picture freezing the image for analysis. Variable speed shutters accommodate various light levels. Lens quality is also important, since lenses can cause image distortion especially when the movement was positioned close to the extremes of the recorded field of view. Therefore, some king of evaluation of the image distortion produced the lens will be required in the methods section.

2.2.2.2 Digitising process

In order to extract from the video recording the quantitative information for further analysis, a coordinate digitiser is needed. This can be obtained as a commercial, freeware or in house program. Whatever is used the digitiser should be checked as part of a routine calibration. During the digitising process, the video image capture board influences the resolution of the video digitiser which has a direct effect on measurement accuracy. Since the digitising process is manual, the operator can also be a source of error. It appears therefore important to examine closely the effect that this digitising process may have on the outcome results. This is discussed later in the text (section 3.3.4.4). With conventional video cameras, the experimenter can skip this digitising phase by using specific software package (e.g. Peak), which automatically detect the markers. This method requires a strong contrast between the markers on the subjects and the background colour. The experimenter still has to check the results in case any lighting artefacts cause erroneous marker recognition. The requirement of good lighting conditions essentially limits this method to laboratory bases studies.

2D kinematic analysis is a common technique used and reliable for movement taking place in a same plan. This is the case in walking or running where the largest motions of the limbs are flexion and extension the sagittal plan. When the movement is occurring within different plans, a 2D representation will be of limited value and a 3D representation of the movement is usually required.

2.2.2.2.1 2D and 3D reconstruction of the data

Several procedures are used to transform digitised coordinates (image coordinates) into a reference frame defined in the two (2D) or three dimensional (3D) space in which the activity occurred. The common method of two dimensional reconstructions is to define a plane, at right angle to the optical axis of the camera, in which the horizontal and vertical references are provided. Once a common origin has been defined, a simple transformation from image to object coordinates can be made.

Dainty et al. (1987) reported a scaling error of no more than 0.5 % of the real distances tested, taking in account that the image plane is parallel to the object plane. This result is however dependant upon specific cameras, subject and distance from camera to object. Therefore the use of combined information from two or more sets of images, can allow a 3D reconstruction of the data. Before any 3D reconstruction can be made, the data has to be synchronised. In contrast to automated motion analysis systems, system using digital video cameras can be genlocked synchronised only by the use of external device. Genlock synchronisation is a technique by which video cameras are synchronised so that video frames in the two (or more) cameras occur at precisely the same point in time.

With digital video cameras, an external event can be chosen to realise a synchronisation between them. However, one can not certify that the time phase is locked between the digital cameras. A time delay up to a frame duration (i.e. 0.02 second for a 50 Hz sampling rate) can occurred between the digital video cameras generating errors in the 3D reconstruction. This may generate some approximation in the position of the 3D reconstruction of the points.

The technique for 3D reconstruction of the coordinates is dependant on the position of the cameras. The simplest approach to 3D data collection involves collection with 90 degrees angle front and side view cameras. The alignment of the camera optical axes at 90 degree simplifies the translation of front and side view XY data to 3D XYZ data. The challenge of 3D data calculation is simply to define the X, Y and Z coordinates for all body landmarks in a movement. In addition to mathematical adjustments for the scale and phase differences between the cameras, mathematical adjustments are required to correct for perspective. Indeed, when body landmark points move into or out of the plane of motion, the single scale factor used in the analysis will provide distorted measures of the motion (Black and Sprigings, 1974).

Developed by Abdel-Aziz and Karara (1971), the direct linear translation (DLT) perspective correction procedure is a mathematically sophisticated approach to 3D data analysis. It is the most popular technique for 3D reconstruction of the coordinates. The primary advantage of the DLT approach is that cameras can be flexibly placed at virtually any location during data collection. As a result, the restriction of our previously discussed 90 degree camera setups (where the optical axes of both cameras must intersect at a right angle) is not present with DLT. Cameras can be aimed at the field of view from almost any angle - thus, data could be collected at a baseball park from 2 cameras placed in the upper decks of the stadium (Shapiro, 1980).

With the DLT, the transformation of image to object coordinates is affected by camera calibration involving eleven or more parameters for each camera. These parameters incorporate the optical characteristics of the camera. The largest restriction of the DLT is the requirement that the control points must be distributed throughout the movement space. Others methods are available that require calibration object smaller than the movement space. They all have greater complexity than the relatively straightforward DLT technique (Ball and Pierrynowski, 1988; Challis, 1995). Other authors proposed additional methods based on the DLT methods to increase the accuracy of the conventional method (e.g. Woltring, 1980 and Hinrichs and McLean, 1995). Woltring (1980) developed a technique that required several views of a two-dimensional calibration structure to perform a 3 dimensional calibration. Hinrichs and McLean (1995) showed that the conventional DLT was more accurate when reconstructing points within the volume delimited by control points.

2.2.2.3 Automated or semi-automated motion analysis system

In contrast to the conventional video cameras, opto-electronic based systems (e.g. Elite, Vicon, Qualisys) allow automated motion analysis, so no manual digitalisation has to be done, at a high sample frequency (up to 1000 Hz). Automated motion analysis generally requires markers to be fixed to the person whose movement is to be analysed. The system will digitise the locations of these markers and so offers the information immediately, whereas semi-automatic ones store the images and then process the data later. The tracking of the markers results from their reflecting properties and the use of sophisticated software (i.e. QTM for Qualisys). With the optical capture system, the 3D reconstruction of the coordinates use complex algorithm based on the DLT methods developed by the corporations. The use of reflective markers requires them to be the brightest objects in the field of view, thus allowing their error free detection. This is achieved either by emission of light of a wavelength to which the markers are sensitive (i.e. Qualisys system), or by using markers that are of a contrasting colour to the subject and background. Such system is reported to be very accurate with as little as 0.8 degree error for a 3D swinging movement (Schotz and Millford, 1993). However, the experimental error is largely dependant on the environmental condition (i.e. lighting conditions, volume calibrated). Other systems are based on the detection of active, infrared light-emitting diode markers, also called activated markers (i.e. Qualisys system) that may be used with optical cameras in an outdoor environment. Since little literature has used the system in such external context, it is still unknown if the system can track the markers without having other bright objects deceiving the data collection. Furthermore, even in the laboratory, the distance of the cameras from the subject is limited, making the recording of a long stride in locomotion as might be seen in cross-country skiing difficult.

2.2.2.4 Pan tilt technique

As above reported the collection of kinematic data involved most commonly the use of stationary video or optical cameras. Both systems limit the volume in which the recorded activity can take place to cover for the collection of accurate and reliable data. For video cameras, large field of view increases scaling and perspective errors, reduces the size of the anatomical landmarks hence affecting the digitising process (Bartlett, 1997). The reliability of motion system using optical cameras is restricted to the calibrated volume. For some sport and exercise movements taking place in wide area (i.e. figure skating or ski jumping), two possible resources exist for quantitative motion analysis; either to use several cameras, and face the problem of splicing information together, or to use a panning technique. Panning is a technique in which a system of video cameras are set-up in and rotated in a tripod to follow the target over time (figure 2.11). This allows a trade-off between a high object resolution and a large field of view.

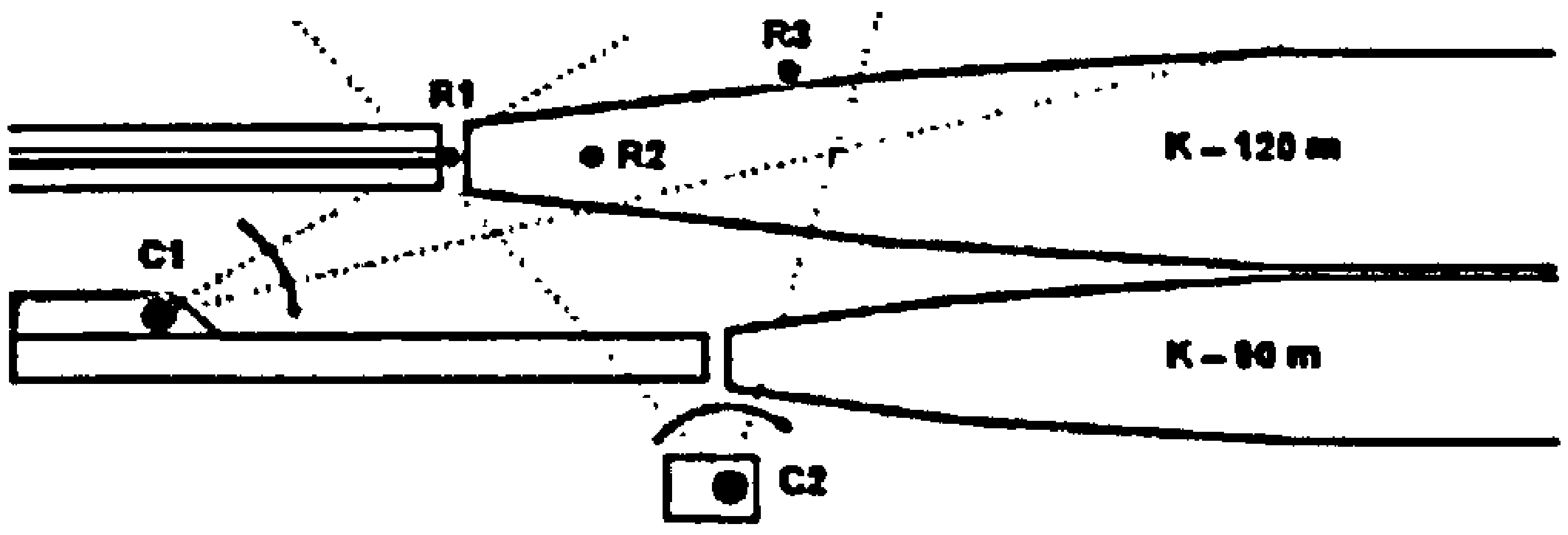


Figure 2.11: example of experimental set up using Pan-Tilt cameras in ski jumping. C1 and C2 stands for cameras 1 and 2. R1, R2 and R3 correspond to the calibration rods (illustration from Virmavirta et al., 2005).

The pan-tilt cameras can be narrowly focused so they provide high resolution imagery but over a large area. By panning a camera with a small field of view, a sufficiently large image size for later digitisation can be obtained while recording all of the activity taken place. The cameras are mounted on tripods equipped with heads incorporating pan and tilt encoders. The optic of a pan-tilt camera is controlled to move in the horizontal (pan) and vertical (tilt) plane (figure 2.12).

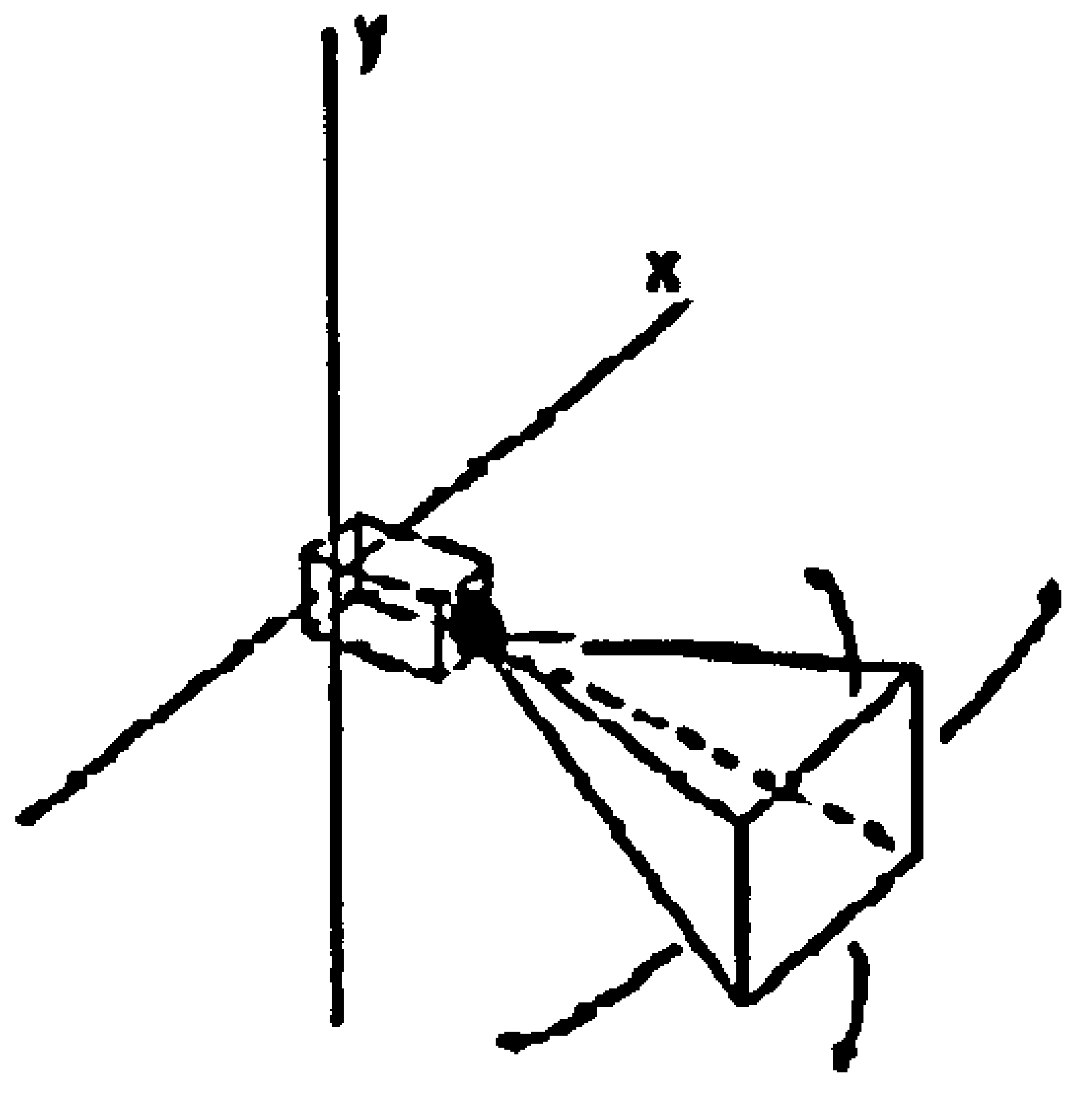


Figure 2.12: Pan-tilt camera motion model. Pan and tilt are modelled as axis aligned rotations around the camera's centre of projection.

The pan/tilt camera motion may be modelled as two idealized rotations around the origin, following by a respective camera transformation (figure 2.12). This transformation can be written as a sequence of matrix operations: $\begin{bmatrix} I_x \\ I_y \\ I_w \end{bmatrix} = CR_Y R_X \begin{bmatrix} x \\ y \\ z \end{bmatrix}$

where $[x\ y\ z]^T$ is a point in world coordinates. A rotation around the x-axis, Rx and then around the y-axis, Ry correspond to tilt and pan respectively. Finally a perspective camera transform, C, results in the image plane coordinates at which the point is observed.

Several techniques have been presented to accomplish 2D and 3D reconstruction of the digitised coordinates for pan-tilt cameras. Gervais et al. (1989) presented a panning technique for two dimensional kinematic analysis using a single panning camera over a field width of 100 m. Yu et al. (1993) presented a panning technique, based on the DLT, in which panning was again restricted to motion about one axis. The advantage of the technique of Yu et al. (1993) is that camera positions do not need to be known; its main disadvantage is that a lot of digitising for camera calibration. Recent improvements in the technique of pan tilt cameras by manufacturers (i.e. Peak Performance Technologies Inc) facilitated the study of the kinematics of various sporting activities requiring large calibrated volume (Moss et al., 2005; Virmavirta et al., 2005). Those researches studied the movement of athletes occurring over a field of view going from 10 to 30 meters.

In DST, cycle length of approximately 5 meters have been reported (table 2.1). All previous research on the kinematic of DST (Gagnon, 1980; Norman and Komi, 1987; Nilsson et al., 2004) has been using protocol involving a stationary video camera. These studies produced relevant kinematic data. Although the recording area required can be see as larger than the one required in walking or running, it may be supposed that the use of pan-tilt cameras does not appear as an essential piece of equipment for the collection of reliable kinematic data.

2.2.2.5 Filtering techniques

Any system used for recording human movement produces some errors that can affect the quality of the data. The previous section highlighted the fact that some errors are generated in the coordinate data of the joints when using digital cameras system. The many potential sources of error in the recording process include: perspective error, parallax error, incorrect identification of anatomical landmarks, digitising errors, digitiser error, camera vibration and calibration errors (Bartlett, 1997).

Many of these errors can be minimised by careful consideration of the experimental procedure but the coordinates will still be contaminated with error.

There are two types of error: systematic and random (D'Amico and Ferrigno, 1990):

- Systematic error is a signal that varies systematically and is correlated in some way with the measurement process.

- The random error is a contamination of the signal that is random in a sense that the error signal is stationary, has a mean value of zero, and is statistically uncorrelated.

The systematic errors are difficult to resolve because the frequency of error lies in the same range as the signal to be measured, but the random error, or noise represents the components of the signal which are not due to the motion measured (Winter 1990). Because the noise is assumed to be random, additive and of high frequency it is recommended to reduce the noise before further calculations and differentiation takes place that will amplify the noise in the signal. The removal of high frequency components from the signal can be achieved using a smoothing process or low-pass filtering. The differences originate from viewing noise reduction from a signal engineering approach (low pass filtering) or a statistical approach (smoothing). Despite different origins, both the low pass filter (e.g. Butterworth filter) and smoothing procedures (e.g. Generalised Cross Validated quintic splines) have been shown to be equivalent (Bartlett, 1997).

There are a number of considerations for smoothing data. Firstly the high frequency components, although reduced, are not completely removed. There is an overlap of signal and noise which means that the low pass filter will distort some of the signal while allowing some noise through (Winter, 1990). Secondly, the low pass filter has to be applied to raw data prior to any non-linear transformation (Bartlett, 1997).

The most common techniques for random noise reduction can be divided into three categories: truncated Fourier series, splines, and digital filters (e.g. Butterworth filter).

Fourier series truncation involves transforming the data from time domain into frequency domain. The data is reconstructed up to the cut-of frequency and the number of terms in the signal are truncated (Bartlett, 1997). The amount of noise removal must be specified, and there have been several approaches that use an objective selection criterion such as Jackson (1979) or Hatze, (1981). For example Jackson (1979) presented a technique based around the examination of the effect of removing Fourier coefficients on the value the second derivative of the residual.

Spline techniques are a series of polynomial curves through one or more points, which are rejoined together at 'knots' in a way which produces an overall smooth continuous function (Woltring, 1985). The process is analogous to taking a set of data in the time domain and drawing a smooth curve through all the data points. The process is often called smoothing because spline fitting produces an approximation to the data that is smoother in appearances than the original. However, smoothing removes the high frequency components from the original data and can be considered to be similar to a low-pass filter. The user is required to define the degree of the splines function (i.e. strength of the filtering process) determines to which derivative level the data will be smoothed to. The use of cross-validated splines is attractive as they determine the degree of smoothing inherently by examining the internal consistency of the data.

Digital filters originate from an electrical engineering discipline (Woltring, 1985) and, therefore, were designed to work on a cyclical signal. They essentially work by taking a series of numbers, applying a number of mathematical operators, which have a weighting coefficient and a time delay, to produce a set of numbers of reduced frequency (Wood, 1982). The weighting coefficients depend upon the desired cut-off frequency. Butterworth filters constitute the most common digital filter. They have been extensively used in biomechanical analyses of human locomotion (Winter, 1990). Normally a second order filter is applied in the forward and reverse directions, resulting in a fourth order filter overall. The use of higher-order filters allow the remove of the phase shift generated by the second order filter and to further reduce the cut-off frequency. Similar to Fourier series, with Butterworth filters the cut-off frequency has to be decided by the researcher. Winter (1990) proposed that some technique (i.e. residual analysis) should be used to select the optimal cut-off frequency. Several techniques have been developed that allow the computation of an 'optimal' cut off frequency based on information about the data, such as the power spectrum and sampling frequency (D'Amico and Ferrigno, 1990; Winter, 1990).

Although filtering is concerned with reducing experimental error, this is not to say that kinematic analysis is error free, error may arise during the acquisition of the video, in the digitising or in the reconstruction of the data. Special care must be taken during the recording of the data in order to minimise these errors and an estimation of the errors produced by the system and the experimenter is important.

2.2.3 Summary

A variety of tools and measurement techniques are used in biomechanics for the recording of human movement. The selection of one or another is dependant on the characteristics of the movement studied and the environmental conditions. In DST, the constraints of the environment, make kinetic analyses, difficult and costly experimental set-up. Similarly, the use of opto-electronic based systems appeared to be difficult with regard to the environmental conditions involved in DST. The use of digital camera constituted a good alternative for the study of the DST movement. Although additional equipment such pan / tilt camera constituted interesting technique for movements taking place into large field, stationary video cameras seemed to be relevant for the study of DST motion.

Video measurement and digitising process will be generator of experimental errors, which will have to be experimentally quantified and processed with relevant filtering techniques.

2.3 Analytical techniques for studying human movement

Alongside the progress of technologies, biomechanists have developed a variety of analytical techniques to further the understanding on human movement and response to the specificities of research areas (Hamill et al., 2006).

This section 2.3 is attempting to present some of the approaches taken for the analysis of human locomotion. In addition to the presentation of the theory behind the various analytical techniques reported, this section 2.3 reviewed the results previously observed in the literature of walking, running and DST.

2.3.1 Qualitative analysis and partitioning of the cycle in human locomotion

Early techniques for analysing human locomotion developed from qualitative analysis of the movement. In those studies, the researcher recognises in the locomotion cycle particular events that can be related to some mechanical purpose or objective in the movement (Knudson and Morrison, 2002). Those events determine the phase in the cycle to be analysed thoroughly with quantitative data (i.e cycle length, cycle frequency, propulsion duration).

Qualitative observation of human locomotion showed that strong differences existed between walking and running that these are two sharply distinct modes of progression. One can see obvious differences between walking and running: the former involves time when both feet are on the ground simultaneously; the later involves periods when both are off the ground simultaneously (i.e. flying phase). However in both walking and running, each leg alternately strikes the ground in an even temporal/spatial rhythm, with an intervening swing phase and support phase. The limbs are opposed in sequence and this characteristic makes them symmetrical gaits. Raidert (1986) reported that the most dynamically stable gait for symmetrical bipeds is the alternating symmetrical phasing in walking and running. As reported in the section 2.1, the DST presents some similarities with walking and running in the sequencing of limb motion.

2.3.1.1 Cycle definition and cycle phases in walking and running

The gait cycle is the basic unit of measurement in gait analysis (Novachek, 1998). In walking and running there is strong agreement on the definition of the components of the respective gait cycles; in the DST a number of different definitions for determining the gait cycle and phases have been proposed, In the analysis of walking and running, the gait cycle has been clearly defined: it begins when the one foot comes in contact with the ground and ends when the same foot contact the ground again (Murray, 1967; Perry, 1992). Basic approaches of gait subdivide the cycle according to the variations in reciprocal floor contact by the two feet. In both gaits the cycle is divided into support and swing phases (Murray, 1967; Dillman, 1975). In walking, the gross distribution of the floor contact is 60% for support and 40% for swing (table 2.2). The support phase starts when the foot meets the ground and ends when the same foot lifts from the ground. This marks the start of the swing phase. Within one leg support phase, a single limb support preceded and followed by a double support phase could be seen. The single limb support phase occurs during 40% of the cycle. The double support phase, being the period when both feet are on the ground occurred twice in the cycle, each representing 10% of the cycle (table 2.2 and figure 2.13). The proportion of support and swing phases in the cycle can also be expressed as the duty factor (Alexander and Jayes, 1980) is an additional cycle parameter to account for the differences between gaits. This represents the fraction of the duration of the stride for which each foot is on the ground. In walking, this value is around 0.6 (Minetti and Alexander, 1997).

In moderate running, the distribution of the floor contact is 35% for support and 55% for swing. The ratios are dependant on the running speed of the athlete. Faster speeds would see a decrease of the contact phase. The toe off occurs before 50 % of the gait cycle is completed (table 2.2). There are no periods when both feet are in contact with the ground. Instead, both feet are airborne twice during the gait cycle, one at the beginning and one at the end of the swing, referred to as a double float (Dillman, 1975; Williams, 1985). The support phase occurs when the foot is in contact with the ground. The toe off marks the beginning of the swing phase in the cycle. Since the proportion of the support phase is smaller in running than in walking, the duty factor is smaller, being around 0.35 (Minetti and Alexander, 1997).

Table 2.2: Proportion of support and swing phases in the gait cycle for a 1.5 m·s-1 walking (data from Murray, 1967) and 3.2 m·s-1 running (data from Novacheck, 1998).

	Floor contact period	
	Walking	**Running**
Support	60%	35%
Initial double support	10%	
Single limb support	40%	
Terminal double support	10%	
Swing	40%	65%

Further division of events and in the cycle phases have been reported in walking and running (Murray, 1967; Perry, 1992; Whittle, 2002). They were determined following their function in the maintenance of the forward progression during locomotion.

In walking, the double support phase (figure 2.13, denominated DS) allows the transfer of the body weight onto the other limb that has just finish swinging, preserving the progression of the body centre of mass. The double support has been divided into two phases: the initial contact (IC) and the loading response (LR) that functionally absorbs the impact force generated at foot contact. The single limb support (SS) preserves the progression of the body until the other foot contacts the ground and can be subdivided into a mid-stance (MST) and a terminal stance (TST). MST is characterised by the time the foot is flat on the ground. TST sees the rising of the heel.

The swing phase allows the forward limb advancement for preparing the next step. Four phases can be reported. The pre-swing (PS) corresponds to the start of the forward movement of the limbs with hip and knee flexion. The initial swing (IS) and mid swing (MS) execute the foot clearance from the ground. Finally, the terminal swing (TS) allows the establishment of the heel first posture (figure 2.13).

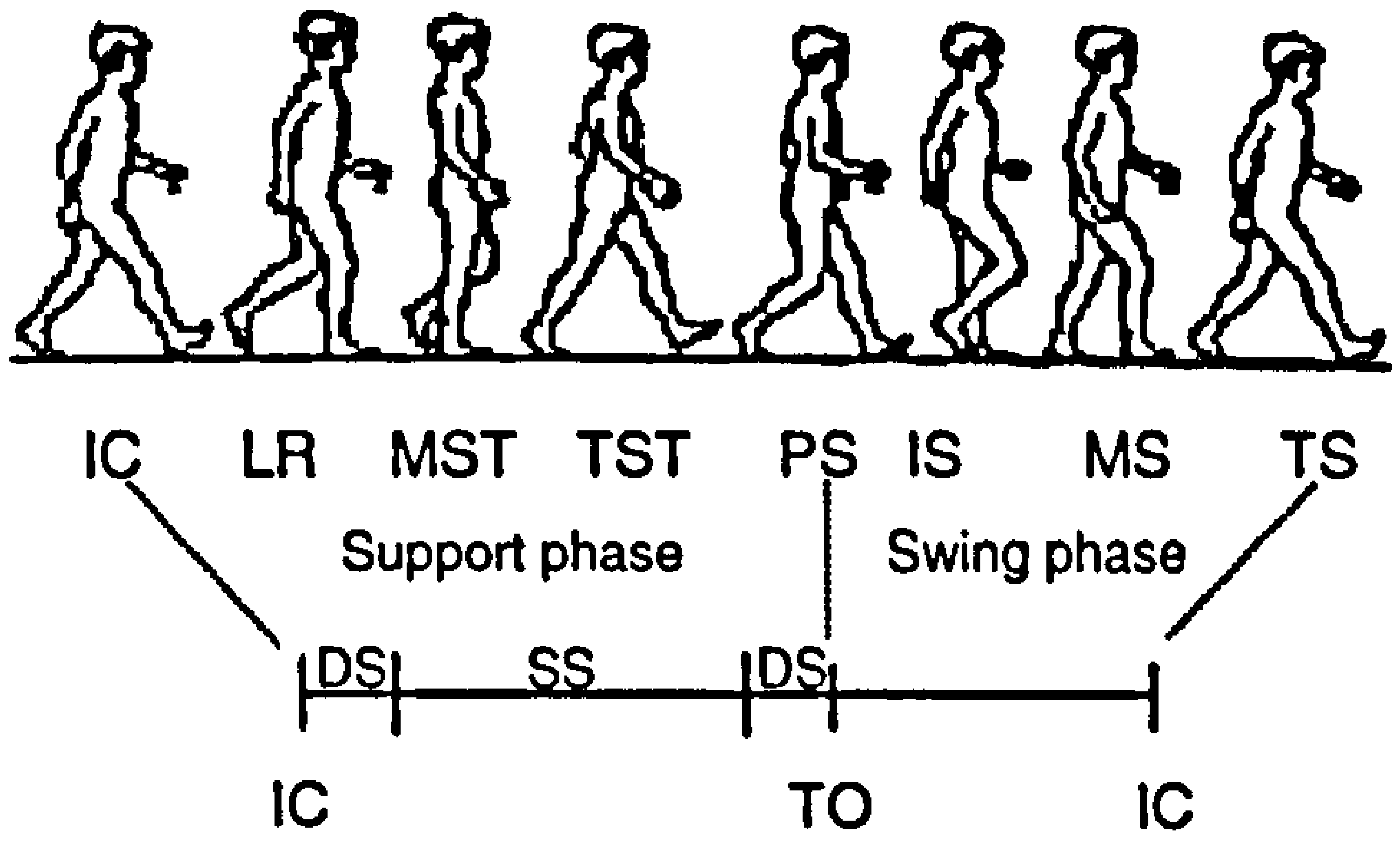


Figure 2.13: The walking gait cycle and functional phases. IC= Initial contact; LR=Loading response; MST=Midstance; TST=Terminal stance; PS=preswing; IS=Initial swing; TS terminal swing; DS=Double support; SS= Single support (from Novachek, 1998).

In running, the support phase can be divided into two functionally different phases. When the foot contacts the ground, a cushioning phase (also called absorbing phase) controls the descent of the body centre of mass from its highest position reached while airborne (figure 2.14). Then, the stance phase is transformed so limbs generate force to propel the body forward. The swing phase, also corresponding to the flying phase, allows the forward return of the limb for realising the next step.

Bipedal running is usually considered analogous to quadrupedal trotting (Alexander, 1977) because it is bilaterally symmetric, and there are two aerial periods per stride.

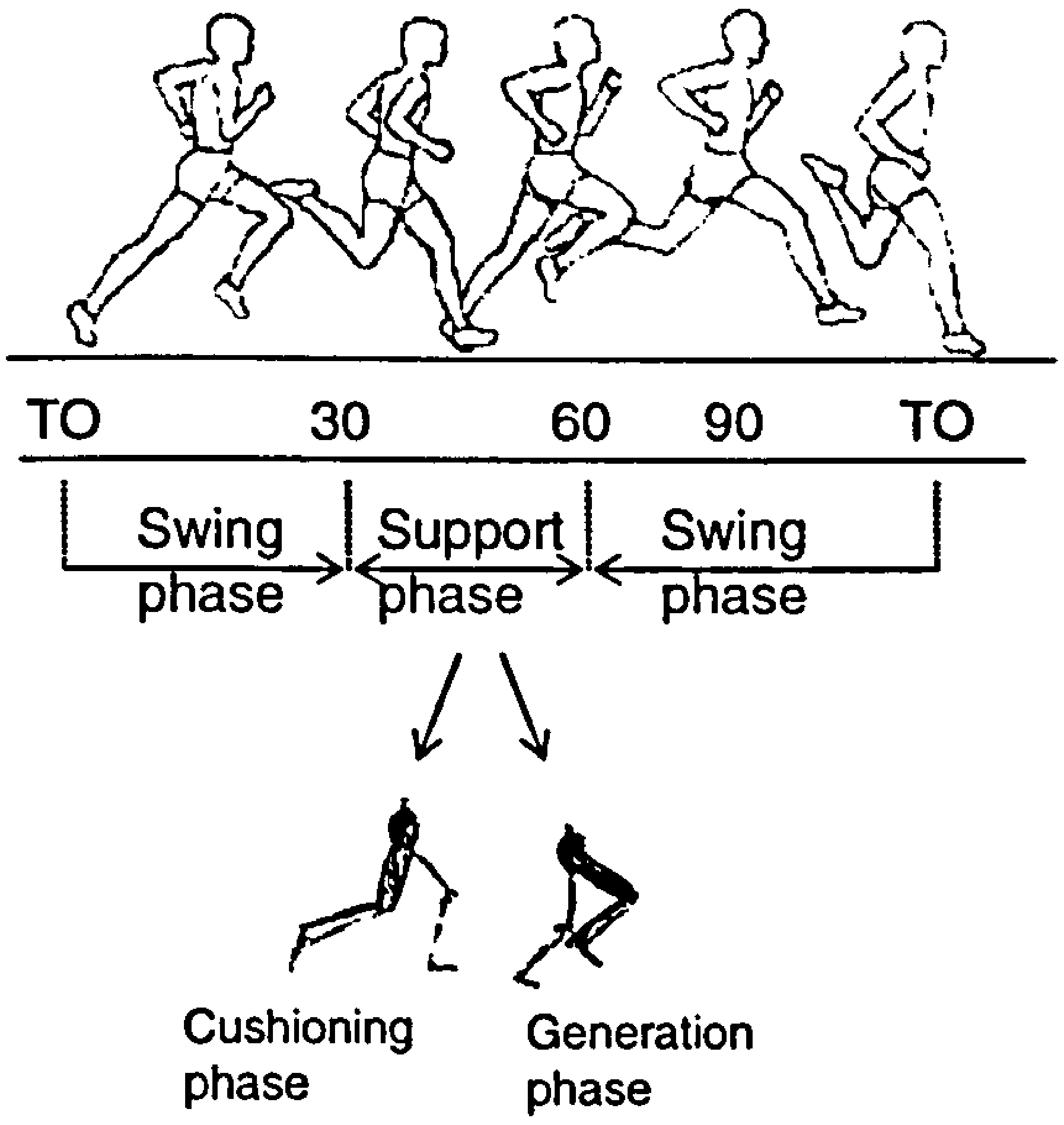


Figure 2.14: The running gait cycle. The support phase can be divided into two other phases. TO= Toe off (from Roberts et al., 1997 and Novachek, 1998).

2.3.1.2 Cycle definition and cycle phases in DST

In contrast with walking and running, some controversies exist on the definition of the DST cycle. Most frequently, the start and end points of the cycle have been defined as occurring at two successive right pole plants (Gagnon, 1980; Roy and Barbeau, 1991; Bilodeau et al., 1992, 1996; Nilsson et al., 2004). In contrast, though they offer no justification for the difference, Marino et al. (1980) preferred to describe the cycle as starting and finishing the moment the right ski lifts from the snow whilst Komi et al. (1982), Komi and Norman (1987) and Norman et al. (1985) defined the start and the end to coincide with the onset of forward movement of the swing leg. Gagnon (1981) and Smith (1992) preferred to define the cycle end points coinciding with the moment that the feet are laterally adjacent.

Regarding the different mechanical objective in the movement of the DST, researchers have proposed the division of the cycle into representative phases: arm and leg propulsion phases and a gliding phase (pure or assisted by poles). Unfortunately, the comparison between studies is still difficult as major differences exist in the phase definitions between authors (Bilodeau et al, 1992; Roy and Barbeau, 1991) (table 2.3 and figure 2.15).

Three different definitions of the leg propulsion phase have been proposed in the cross-country skiing literature (table 2.3, figure 2.15). Komi (1987) showed that the application of maximum vertical and horizontal ski forces occurs within the period between the moment the skier has his feet laterally adjacent and the moment the ski lifts from the snow (figure 2.15). This result led to the consideration that the leg propulsion phase definition proposed by Dillman (1979) and recently used by Bilodeau et al. (1992) and Nilsson et al. (2004) is representative in the DST movement of the leg forces application period.

Table 2.3: Summary of the definition of the leg propulsion phase, gliding phase, swing phase and arm propulsion phase reported in previous studies.

	Leg propulsion phase	Gliding phase	Swing phase	Arm propulsion	Observations
Gagnon (1980, 1981)	Feet adjacent (1) to beginning of the recovery leg (4). 44%	Pure glide: of the recovery leg (4) to ipsilateral pole plant (5). 12 %	-	62% (no written definition)	Cycle
Dillman et al. (1979), Norman and Roy (1985)	Feet adjacent (1) to lift of central part of the ski (3) 20-25 %	30% (no written definition)	-	-	Half cycle
Marino et al. (1980)	50% (no written definition)	17% (no written definition)	-	32% (no written definition)	Cycle
Komi et al. (1982)	36-48 % (no written definition)	27% (no written definition)	-	-	Half cycle
Roy and Barbeau (1991)	Contralateral pole lifts from the snow (2) to the lift of the central part of the ski (3). 22-27 %	Pure glide: lift of central part of the ski (3) to ipsilateral pole plant (5). 24-38%	-	Pole plant (5) to its lift from the snow (8). 57% to 70%	Half cycle
Bilodeau et al. (1992) Smith (2003)	Feet adjacent (1) to lift of central part of the ski (3). 13%	(no written definition). 30%	(no written definition). 38%	Pole plant (5) to its lift from the snow (8). 35 %	Cycle
Nilsson et al. (2004)	Feet adjacent (1) to lift of central part of ski (3). 14%	Feet adjacent (1) to next one (7). 48%	Lift of the central part of the right ski (3) to right ski plant (6). 29	Pole plant (5) to its lift from the snow (8). 34%	Cycle

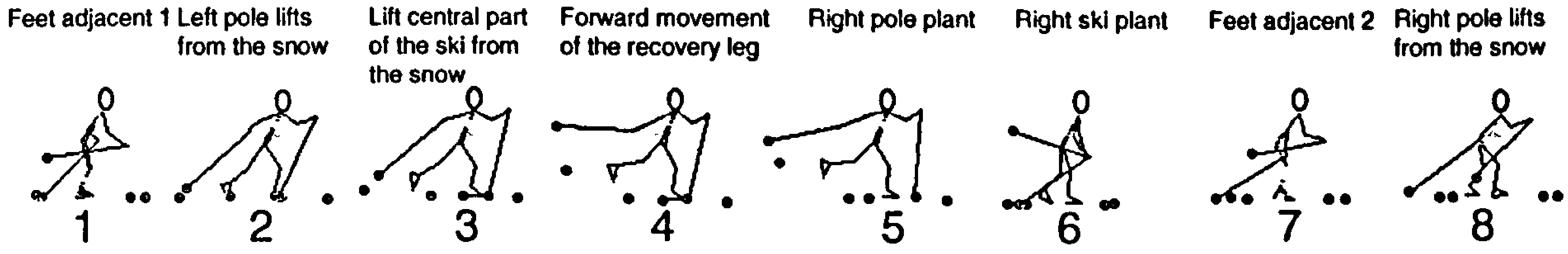


Figure 2.15: Summary of all the events used by previous authors to define leg and arm propulsion phases, gliding phase and swing phase.

Gliding length has been reported to be an important component of the total stride length (Marino et al., 1980; Smith, 1992). As the skier is continually gliding from one leg to the other, it makes it difficult to determine the start and the end of the gliding phase. Most of the authors have proposed their own definition. One described a "pure gliding phase" as the period when the skier is gliding without exerting any propulsive forces (Gagnon, 1980, 1981; Roy and Barbeau 1991). Others described an "assisted glide phase" as the period the skier is gliding with simultaneous upper body propulsion (Bilodeau et al., 1992) (table 2.3). This lack of consistency and justification for the gliding phase definition shows the difficulty of characterising glide within the cycle and question its reliability in the study of the DST cycle.

In order to broaden the analysis of the motor control in the DST locomotion, Bilodeau et al., (1992) and Nilsson et al., (2004) proposed a phase partitioning dividing the cycle into a swing phase and a propulsion phase (table 2.2). The relevance of this phase division was strengthened by previous biomechanical observations on the swing and propulsion phases (Gagnon, 1980; Komi and Norman, 1987). These authors reported that both of these phases were important in the production of skiing velocity.

No consensus was reached regarding the definition of the gliding phase between the authors. The division of the cycle into swing and propulsion phases (Bilodeau et al., 1992; Nilsson et al., 2004) is relevant regarding the walking and running cycle division (Murray, 1967; Whittle, 2002). The "ski lift from the snow" event seems to be adequate for the determination of the swing and support phases in DST.

However, regarding the DST literature, a more detailed subdivision of the phases is required to further analysis the mechanical roles of the motion.

2.3.1.3 Analysis of the control of speed in walking and running

Depending on the gaits used, the maximum velocity achieved can be different. In walking, the speed ranges from 0.6 to 3.0 $m \cdot s^{-1}$ with a mechanically limited speed (refer to paragraph 2.3.4.1.2). To go faster, humans change their gait to a running movement making possible an increase speed of up to 10 $m \cdot s^{-1}$. In quadrupedal locomotion, animal galloping generates speed up to 20 $m \cdot s^{-1}$ (for horses). Within the gaits the change of speed is regulated by cycle length and cycle frequency, velocity being the product of these spatial and temporal components. The increase of all gait speed is achieved with an increase of both cycle frequency and cycle length. Because gait parameters are velocity dependent (Grieve and Gear, 1966) the characterisation of gait must be studied with this dimension (Andriacchi et al. 1977). Therefore, the changes in gait pattern over the full range of practical speeds are of utmost importance in functionally characterising gaits (Rosenrot et al., 1980; Hay, 2002).

Furthermore the investigation of the control of velocity reflected the neural system regulation (Grillner, 1979, Nilsson et al., 1985).

Whereas in the DST, contradictory results have be observed in the literature (Gagnon, 1980, 1981; Roy and Barbeau, 1991; Nilsson et al. 2004), walking and running literature showed consistent findings. Specific mechanisms for regulating speed can be observed in walking and running that develop from the characteristics of the gaits.

2.3.1.3.1 Cycle frequency

The cycle frequency (i.e. inverse of the cycle duration) is modified when gait velocity is increased. Cycle frequency (CF) is increased in a concave curvilinear manner as the velocity of walking and running increases (figure 2.16). In running, relatively small increases in CF are made as the velocity is discretely incremented at lower speeds (3-6 $m\cdot s^{-1}$ for running), gait velocity is increased from a moderately fast pace to maximum (6-9 $m\cdot s^{-1}$) proportionally greater increases are observed in CF (Dillman, 1975; Williams, 1985). In agreement with this, Cavanagh and Kram (1990) reported specifically for distance running speed (3 to 5 $m\cdot s^{-1}$) a very low fluctuation of CF. Therefore, depending on the range of speeds investigated in running, a different change in CF can be reported. In walking, the curvilinear trend of the CF versus cycle velocity is less pronounced in comparison to running. Many authors (Dillman, 1975; Williams, 1985; Hay, 2002) represented the empirical relationship between CF and cycle velocity over a wide range of velocity. Agreement between researchers has been found for a parabolic equation of the type $CF= aV^{0.5}$ (a and V represent a constant and the walking or running velocity) for walking and running (Zatziorsky et al., 1994). For walking, Wagenaar and Beek, (1992) proposed the following relationship $CF = 0.41V^{0.5}$. Whereas similar changes in CF were observed in walking and running, with velocity increase, the increase in CF was more pronounced in walking than in running (Nilsson et al., 1985).

In quadrupedal walking and trotting, cycle frequency has been found to linearly increase with speed within a gait. Heglund et al. (1974) found that for trotting, there was an approximate 50% increase in CF for a doubling in speed. In contrast, in galloping a relatively constant stride frequency with increasing velocity have been observed.

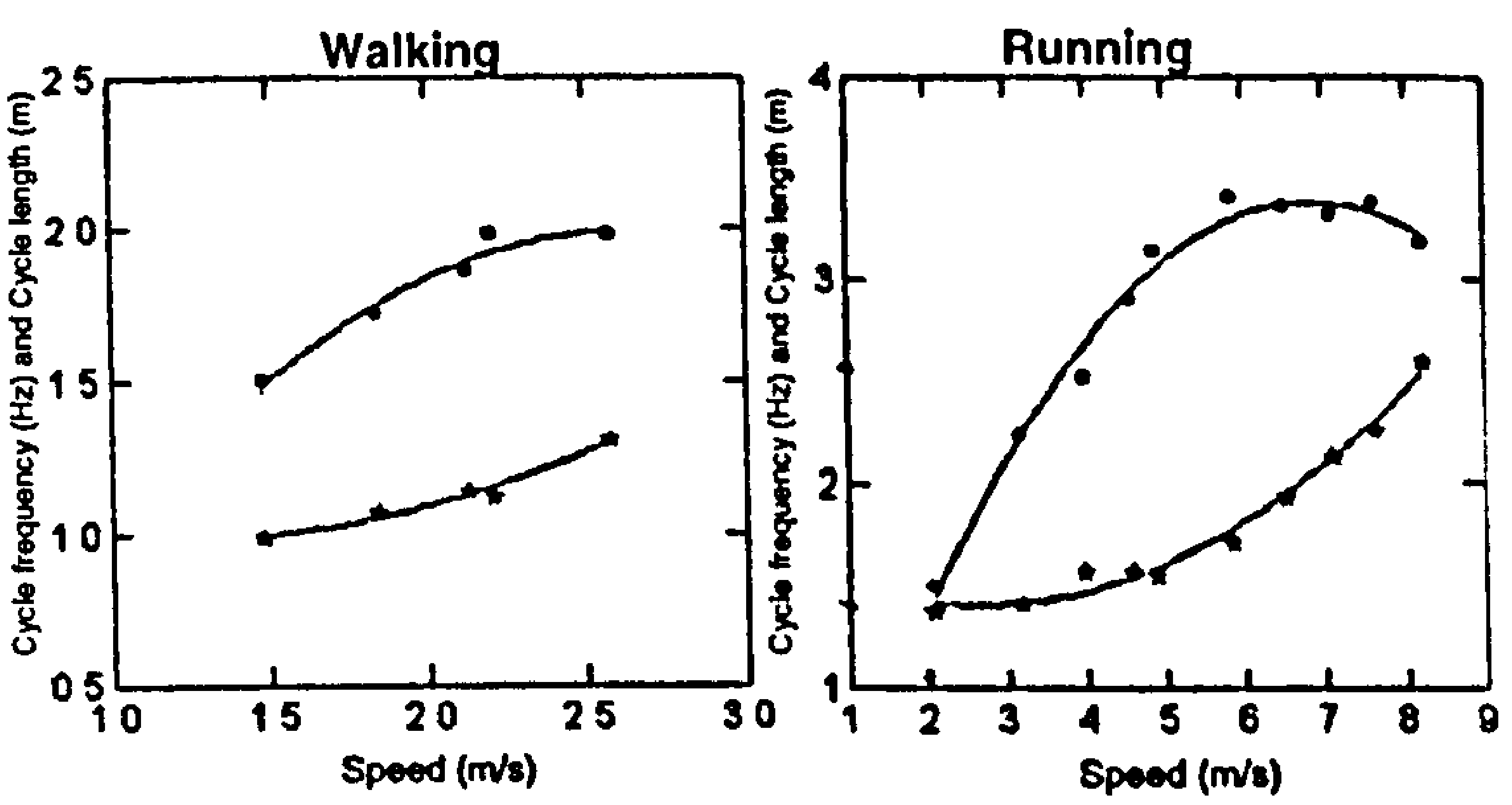


Figure 2.16: Cycle frequency (CF) and cycle length (CL) change with speed in walking and running (from Hay, 2002).

2.3.1.3.2 Cycle length

Cycle length (CL) is greatly increased as speed increases. The pattern of CL versus speed showed a convex curve down reaching a maximum value toward the upper end of the speed range (figure 2.16). In contrast with CF, relatively large linear increments are made in stride length as speed is discretely increased at the lower velocities (up to 2.2 7 m·s^{-1} for walking; up to 7 m·s^{-1} for running) (Dillman, 1975; Williams, 1985). As the walker and the runner reach distinct higher speeds there is relatively little change in the CL. In running, some investigators report slight decreases in CL at maximal running speeds (Saito et al., 1974) (figure 2.16). The limitation of the CL at higher velocity resulted from the reach of the maximum joints angular range of motion of the lower limb (Williams, 1985).

In walking, the relationship between step length and step frequency is approximately linear over a broad range of walking speeds, meaning that this relationship may be an invariant of walking. More generally, the relationship CF-versus velocity and CL versus velocity has been reported to be consistent in much cyclic locomotion such as walking, running, hopping, retro-walking and swimming (Hay, 2002). In contrast, in quadrupedal gait, a linear relationship between cycle frequency and cycle velocity has been reported, showing differences between bipeds and quadrupeds. This probably resulted from the fewer possibilities of cycle length increase in quadrupeds compared to bipeds.

Table 2.4: Modification of the temporal cycle parameters with increasing velocity

	Cycle Frequency	Absolute			Relative		
Gaits		Support	Double Support	Swing	Support	Double Support	Swing
Walking	Curvilinear ↑	↓	↓	↓	↓	↓	↑
Running	Curvilinear ↑	↓	-	↑	↓	-	↓

2.3.1.3.3 Change in swing and support phases

As the cycle duration diminishes with the increase in velocity, the support and swing phase duration will be modified. Table 2.4 illustrates the different change in temporal cycle parameters with increasing velocity. In walking, one can observe that the increase in velocity results in decreasing the absolute support, double support and swing durations. In running, whereas the absolute duration of the support phase also decreases, the absolute swing phase duration increases for velocities up to 5m/s and slightly decreased for higher speeds. The increase of cycle frequency with velocity increase was mainly caused by a constant decrease in the support phase (Nilsson et al., 1985). Differences between walking and running can also be noticed in the changes of the relative support and swing duration (i.e. support and swing phase expressed as a percentage of the cycle duration) with increasing velocity. Relative support duration and double support duration for walking decrease with velocity increase in both gaits. Related to these observations, the duty factor is lower in both gaits with the augmentation of velocity (Minetti and Alexander, 1997). While in walking the relative swing phase augmented with increasing velocity, in running the relative swing phase decreased with increasing velocity. At high velocity walking, the double support phase practically disappears, leading to a transformation into running (Zatsiorsky et al. 1994). Furthermore, the increase in the relative swing duration results from the fact that in walking, longer steps are generated and that the support phase is restrained. Values of support time are drastically lower in running than walking because of the way the foot contact the ground.

The support length appears to increase continuously with increasing velocity, in running whilst levelling off at speeds of approximately 2.0 $m \cdot s^{-1}$in walking. This results from the fact that in walking the contralateral stride length reaches maximum amplitude at similar speed (table 2.5).

Table 2.5: Modification of the spatial cycle parameters with increasing running velocity

Gaits	Cycle Length	Absolute	
		Support	Swing
Walking	↑ low velocity → high velocity	↑	↑
Running	↑ more for smaller velocity	↑	↑

2.3.1.4 The control of speed in DST

As previously reported, the determination of the mechanisms for controlling velocity in human gait is of importance for characterizing functionally the locomotion and investigating the neural system regulation. Although a large number of studies have analysed the control of speed in walking and running, in the DST, very few studies have investigated the cycle change with increasing velocity (Gagnon, 1980, 1981; Roy and Barbeau, 1991; Nilsson et al. 2004). Gagnon (1980, 1981) reported a decrease in cycle duration and a rather constant cycle length with velocity increase (from 4.47 to 6.79 m·s^{-1}). Nilsson et al. (2004) presented a very accomplished study in cross-country skiing, looking at the cycle temporal patterns with increasing speeds from slow to fast (from 3.1 to 5.0 m·s^{-1}). In accordance with Gagnon (1980, 1981) the authors reported a significant increase of the cycle frequency across the speeds for the DST, whereas the cycle length did not increase continuously to the maximum speed level. The authors found a strong correlation between the cycle velocity and the cycle rate but a weak correlation between cycle velocity and cycle length. This behaviour has been observed in every classical and freestyle technique. In contrast, Hoffman et al. (1995) and Nilsson et al. (2004) reported that at maximal velocities (reaching 6.8 m·s^{-1}), although the cycle rate was still increasing, the cycle length was slightly decreasing in reference to submaximal velocities. Smith (2003) concluded that velocity in cross-country skiing can be thought to be mainly controlled through adjustment of cycle rates.

In contrast with Smith's statement, a study from Roy and Barbeau (1991) showed a 16 % increasing of both cycle length and cycle frequency for an increasing velocity from 3.5 to 4.85 m·s^{-1}. These differences between studies may result from different factors such as the experimental protocol, the snow conditions or the skier level. More experiments are therefore needed to reduce this indecision in the literature.

2.3.1.4.1 Absolute phase durations

Increasing skiing velocity produced large decreases in absolute propulsion phase duration (Gagnon, 1980, 1981; Roy and Barbeau, 1991; Nilsson et al., 2004) and absolute gliding phase duration (Gagnon, 1980; 1981; Nilsson et al., 2004). This decrease of the absolute propulsion duration with increasing velocity reduces the possibility for the skier to generate a large enough leg force impulse. It may reduce the capability of the neuromotor system to co-ordinate the muscle action so that the propulsion of the arm and leg muscles occurs exactly at the right time in the movement cycle and with large enough movement amplitude (Nilsson et al., 2004). Therefore, the maximal velocity in the DST may be limited by the speed of muscle contraction rather than the physiological energy delivery system (Hoffman and Clifford, 1992; Nilsson et al., 2004). Depending on the terrain, in order to increase their velocity, skiers may have to change their technique for a double poling involving larger upper body masses (Smith, 2003). The absolute swing phase duration was also observed to decrease with increasing velocity (Nilsson et al., 2004).

2.3.1.4.2 Relative phase durations

Considering the relative duration of the propulsion (i.e. expression of the phases as a proportion of the cycle), swing and gliding phases Nilsson et al. (2004) showed no significant changes with increasing velocity. Additionally, the onset and termination of the propulsion, swing and gliding phase durations did not change. Results from Gagnon (1981) revealed a similar tendency. Nilsson et al. (2004) proposed that the constancy in the relative phase durations could be an invariant feature of the DST. This result was derived from the fact that similar behaviour was observed for other cross-country skiing techniques. Nilsson et al. (2004) proposed that a constant duration would facilitate the neural system to control the movement. Conversely, Roy and Barbeau (1991) found a decrease in the relative leg propulsion phase with increasing velocity. Disparities in the results between these studies may result from difference in the definition of the leg propulsion phase (see table 2.3, section 2.3.1.2), since similar subjects were tested. Therefore, constancy in the relative phase duration needs to be confirmed with further studies.

2.3.1.4.3 Cycle and phase lengths

Considering the phase lengths with increasing velocity, Gagnon (1981) observed tendencies for a decrease in the leg propulsion and gliding lengths whereas Roy and Barbeau (1991) reported a constant distance travelled during the leg propulsion phase and an 85% increase of the gliding distances. Roy and Barbeau (1991) proposed that a higher gliding distance resulted from a more "efficient propulsion" phase, thus, larger leg force applied. This has been confirmed by Komi (1985), showing that the peak vertical and horizontal forces of the propulsion phase increased with the increase in the skiing velocity.

To summarise section 2.3.1; qualitative and cycle and phase analyses represented a first level of investigation for characterising locomotion. These investigations allowed for the discrimination of the various human locomotion types and the reporting of the strategies for controlling speed.

However, qualitative and cycle analytical technique for the study of human movement cannot report the segmental organisation (i.e. technique) used to generating the displacement of the body in the DST. Therefore another level of kinematic analysis is required to account for the description of joint angular movement.

2.3.2 Joint angular kinematic analyses of human locomotion

Joint angular motion constitutes a higher level of analysis used by researchers for describing and characterising locomotor pattern. This approach allows a determination of the joints movement occurring during the locomotor motion and, to some extent, of the role of joints in the overall displacement of the body. The angular joint profiles have been largely investigated in the literature of walking and running (Murray, 1967; Mann and Hagy, 1980; Nilsson et al., 1985; Novacheck, 1998). In contrast, the joint kinematics of the DST remains very poorly described with only a few studies analysing a small number of subjects (Gagnon, 1980; Komi et al., 1982; Komi and Norman, 1987). The differences in the joint kinematic patterns allowed a determination of the role of the segment for maintaining forward displacement.

As more literature has been undertaken on walking and running than on the DST, an emphasis of this section will be towards the differences existing between walking and running. Comparison with the DST joint kinematics will be made when sufficient data has been reported in the literature.

2.3.2.1 Joint Angular patterns in walking, running and DST

For any cyclic locomotion, the swing phase and support phase showed phases of flexion and extension of the lower limb (Grillner, 1979). Although the same back and forth movement exist in human gaits, similarities and differences in the joint angular patterns can be reported between walking, running and DST.

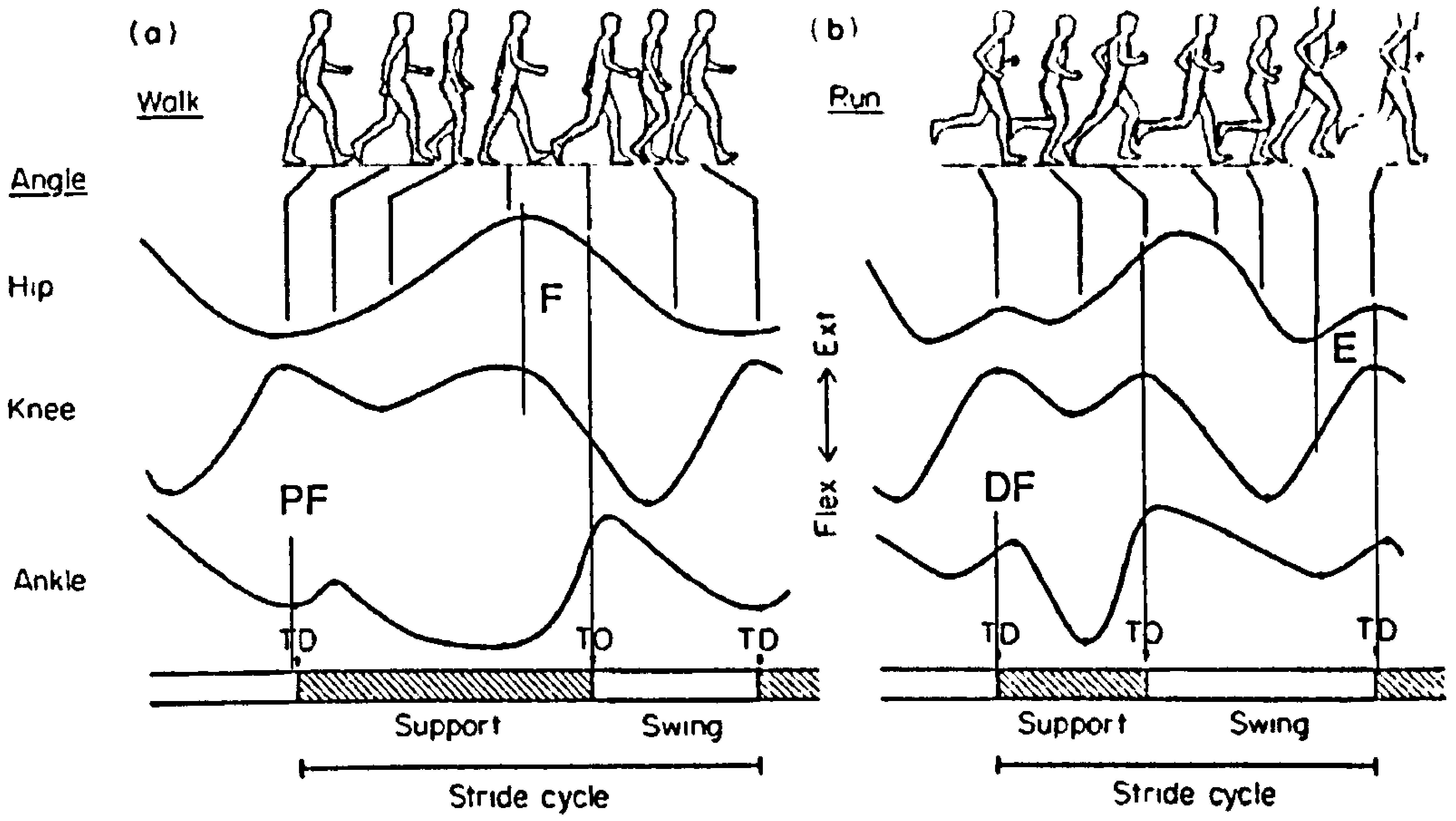


Figure 2.17: Hip, knee and ankle patterns in walking and running (from Nilsson et al., 1985); TD= touch down; TO= toe off.

The hip and knee angular patterns of walking and running have been reported as being very similar, although differences can be observed. At high speed, the hip amplitude can be 4 times larger in running than in walking. This larger amplitude is essentially the result of a larger hip flexion in running during the first part of the swing phase. In contrast, the maximum hip extension at the end of the support phase is consistent between walking and running, but occurs slightly later in the running cycle (i.e. at the time of the toe off) (Novacheck, 1998). A specific feature of the hip in running is that it extends during the second half of the swing phase in preparation for initial contact (Figure 2.17, quoted E).

On the other hand, a typical feature of walking showed the flexion phases of the hip and knee joints starting before the foot has left the ground (Nilsson et al., 1985) (figure 2.17, quoted F). In running, the flexion phase of the hip and knee starts after the foot has left the ground. As observed for the hip, larger knee flexion amplitude was observed in running than in walking (Nilsson et al. 1985). This last observation mainly flows from a larger knee flexion during the swing phase in running that can reach 130°, in comparison to 60° in walking.

Another feature specifies the running gait. During the absorption phase of the stance phase, the knee flexes to approximately 45 ° whereas in walking the knee stays relatively straight during the stance phase. In contrast, the following knee extension during the second part of the stance phase showed larger values in walking than in running.

In contrast to the resemblance existing between the hip and knee angular patterns, the motion at the ankle joint change considerably when walking and running are compared. In walking there is a plantarflexion at initial foot contact (because of the position of the tibia) (figure 2.17, quoted PF) followed by progressive dorsiflexion whereas in running a dorsiflexion (figure 2.17, quoted DF) occurs at the time of initial ground contact, and then progresses to a plantarflexion as the body weight is transferred to the stance leg. Since the ground reaction force was much larger in running than in walking (Keller et al., 1996), the demand on the lower limb was larger, generating longer period of anterior and posterior compartment muscles activation in running than in walking (Nilsson et al., 1985).

In the DST there is a great need for describing and analysing the joints' angular profiles. Although, Komi et al., (1982) reported hip and knee angular patterns they only reported the results from two subjects without discussing the mechanisms for maintaining forward displacement. Gagnon (1980) detailed the knee angle pattern during the recovery phase. Discrete angular data (i.e. maximum flexion, maximum extension) have been reported allowing the calculation of lower limb joints range of motion which represents an overview of the contribution of the segments during a full cycle. The range of motion constitutes a rather simplistic but effective mean for comparing locomotions. Data from Gagnon (1980), Komi et al., (1982) and Komi and Norman (1987) showed lower values of knee range of motion in the DST but similar values of hip range of motion compared with similar speed running (table 2.6).

In walking and running the knee is flexed when the legs swing forward in order to avoid the foot being caught on the ground in the former and for the later to reduce the leg moment of inertia (Novachek, 1998). In contrast, skiers may be able to maintain the swinging leg straight, sliding the ski on the snow. The DST literature provided no literature detailing the behaviour of the ankle joint in the DST.

Table 2.6: Range of motion of hip, knee and ankle joints for a full cycle reported in the DST, running and walking.

	DST **(4.8-$6\ m\cdot s^{-1}$)**	**Running** **(3-$6\ m\cdot s^{-1}$)**	**Walking** **(1.5-$2.2\ m\cdot s^{-1}$)**
Hip	60-85°	60-75°	40-48°
Knee	20-30°	90-103°	55-65°
Ankle	-	48-54°	30-35°
	Gagnon (1981) Komi et al. (1982) Komi and Norman (1987)	Milliron and Cavanagh (1990) Nilsson et al. (1985)	Murray (1967) Perry (1992)

2.3.2.2 Ankle joint function

The differences in the ankle joint between walking and running develop from the distinct function of the foot in the cycle. The understanding of the foot function in both gaits needs further details relative to the ankle angular motion and muscle activation.

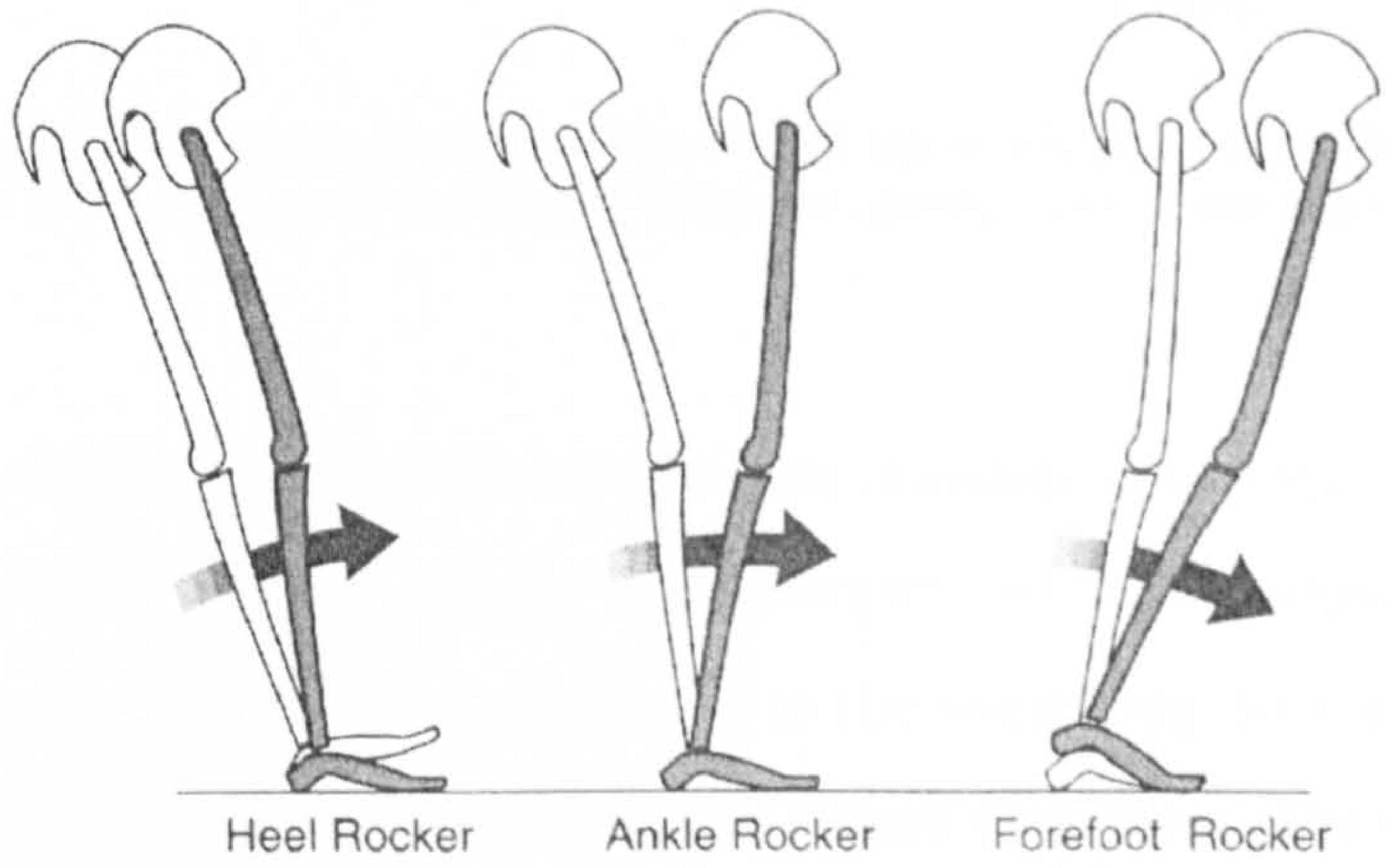


Figure 2.18: Representation of the foot functions during the support phase in walking (from Perry, 1992).

Considering walking, the complex ankle joint-foot creates a pivotal system that allows the body to advance while the knee maintains a basically extended posture. The heel and toe style of walking enables us to keep our knees relatively straight, while the feet are on the ground.

More precisely, during the loading response (LR, figure 2.13) anterior compartments of the lower leg decelerate the rate of ankle plantar flexion generating a forward movement of the tibia (i.e. rolling advancement of the body weight on the heel, termed heel rocker in figure 2.18). The restrained ankle plantar flexion during LR acts also as a shock absorber. During the mid stance (MS), the ankle motion creates an increasing dorsiflexion that rolls the tibia forward (i.e. ankle rocker in figure 2.18). During the terminal stance (TS), the combination of ankle dorsiflexion and heel rise places the body centre of mass anterior to the source of foot support, increasing the heel rise (i.e. heel rocker). This creates a free forward fall situation that passively generates the major progression force in walking.

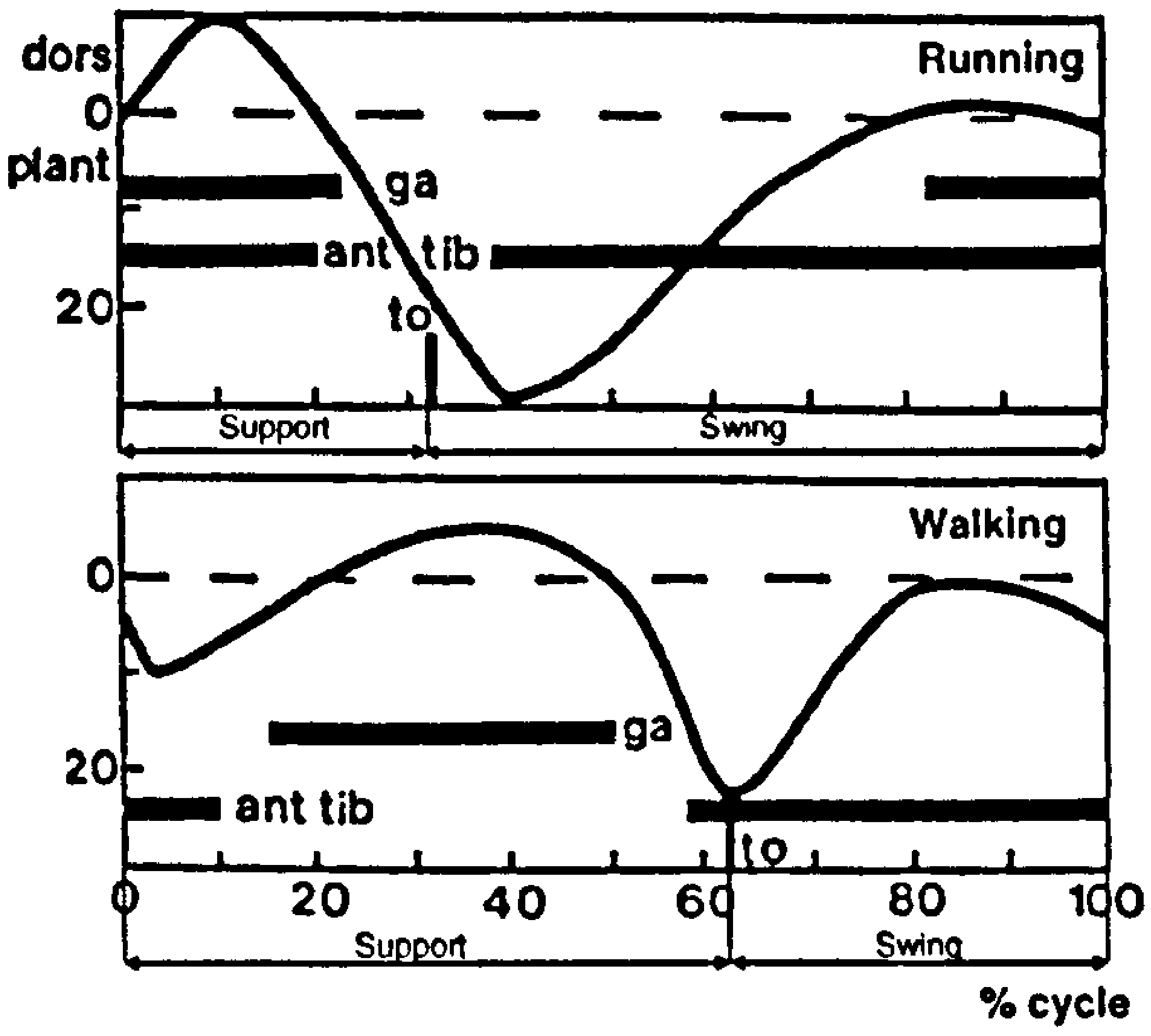


Figure 2.19: Angular pattern and muscle activation of the ankle joint in walking (1.34 m·s^{-1}) and running (5.4 m·s^{-1}) (From Mann and Hagy, 1980); ga=gastrocemius; ant tib= anterior tibial; to= toe off

Considering running, greater ankle dorsiflexion is required to achieve initial foot contact. In contrast to walking, during the absorption phase of running the ankle dorsiflexes as the body weight is transferred to the stance leg. In running the ground reaction force during the stance phase reaches more than three times the body weight (Nilsson and Thorstensson, 1989; Novatchek, 1998). Thus, the cushioning phase is a very important component of the cycle in order to avoid injuries. The ankle dorsiflexion phase acts in collaboration with flexion of the hip and knee joints as a shock absorber (Mercer et al., 2002). Although the shock absorber mechanism is more important in running than in walking (i.e. because of the large force recorded at the landing foot), both locomotions present a similar one.

The presence of shock absorber mechanism is confirmed by the observation that the extensor muscles of the limb are activation prior to the foot contact in preparation for the stiffening of the leg at landing (Mann and Hagy, 1980) (figure 2.19). Whilst this is relatively minor in walking, in running the muscles are lengthened during the cushioning phase, contributing in absorbing energy from the falling body. The elastic properties of the muscles allow a restitution of the energy during the generation phase.

In the DST, we may expect that the ankle might have a different role from those observed in walking or running. Indeed, the locomotion is subjected to the cumbersome nature of the ski and the gliding phase. This may modify the behaviour of the shank in reference to the foot. In addition, there is no obvious impact event to require significant shock absorption.

2.3.2.3 Changes in the joint kinematics with velocity increase in walking, running and DST.

The importance of the study of joint angles in the understanding of human locomotion may be illustrated with the testing of different speeds in walking and running. In doing so, it is also possible to report the techniques used by humans to increase speed in various locomotion.

In addition to the adjustment observed (section 2.3.1.3) on the cycle, the increase of velocity is achieved through a modification of the movement patterns. Because of the different nature of the gaits, the change of velocity is achieved by different means. Considering the hip, some changes in the joint flexion and extension amplitudes were observed in both walking and running (Nilsson et al., 1985), though, the overall increase of the hip amplitude was mainly accomplished by an increase of the hip flexion angle during the second part of the swing phase. In walking, the increase of hip extension with increasing velocity occurs before the toe lifts from the ground whereas in running, this occurs at the beginning of the swing phase.

Whereas the knee flexion magnitude was markedly increased in running during the swing phase, no increase in the knee flexion magnitude was observed in walking at speeds above 1.5 $m \cdot s^{-1}$. At slower speeds, the increase of the knee flexion remained relatively modest.

Larger plantarflexion of the ankle at foot-off was reported with velocity increase in both walking and running. In running, this generates the major part of the amplitude increase of the ankle, allowing the application of a larger propulsion force so important for achieving greater velocity (Weyand et al., 2000). In contrast, in walking the larger ankle angular amplitude developed from increase in the maximum ankle dorsiflexion during foot contact. This motion allows a longer step length whilst maintaining a relatively straight leg. The overall period of time in which there is activity changes considerably as the speed of gait increases. Comparison of walking and running at the same speed shows that the ground reaction force was larger in running than in walking (Keller et al., 1996), which is similar to running at speeds between 3 and 8 $m \cdot s^{-1}$. Differences are explained by the fact that subjects adopted a higher centre of gravity excursion due to the flight phase in running, increasing the downward velocity of the body centre of mass at foot strike. In running, the increase of velocity is achieved mainly by exerting greater force rather than increasing the angular velocity of the limbs (Weyand et al., 2000). In walking, a good correlation in the horizontal and vertical ground reaction force peaks was observed with velocity increase (Andriacchi et al., 1977; Winter, 1991). Since some modification of the joint angular amplitudes occurred in walking and running with increasing velocity, one can expect some effect on the mechanics of locomotion.

The literature of walking and running provided a strong background on the description of the joint movement during the cycle and of the relative changes when speed was modified. In contrast, the joint angular kinematics of the DST has been very poorly studied, providing mostly qualitative information on the segmental strategy used for increasing velocity. Previous study has showed that the increase of the leg propulsive force resulted from a more flexed body position (trunk, knee and ankle) of the skier at the beginning of propulsion (position feet adjacent) which favours the storage of elastic energy (Roy and Barbeau, 1991). It has also been suggested that the larger flexion of the trunk and knee at the end of leg propulsion produces a better orientation of the propulsion force. In addition, the larger forward inclination of the pole plant at higher velocities may increase the proportion of propulsion force (Gagnon, 1980, 1981).

To summarize, section 2.3.2 showed that in locomotion such walking and running the time-angle patterns developed from specific functions of the joints. In DST, the lack of kinematic data detailing the movement prevented the understanding of the role of the joint in the production of forward displacement. Therefore, any further analysis of the DST shall be describing the upper and lower joint movement patterns.

2.3.3 Coordination analysis of human movement

The human body is composed of a large number of segments that need to be efficiently coordinated in order to perform a specific task. Bernstein (1967) suggested that coordination is the result of mastering the redundant degrees of freedom of the action system in order to conserve only those that are functional for the realisation of the task. This dimensional reduction converts a complex system into a task-specific flexible coordinative structure, which is characterised by its invariant topology and its easy control via a small number of variables (Turvey, 1990). The reduced dimensionality / complexity of the motor system encourages the development of functionally preferred coordination. This coordinative structure enables the organism to achieve (a) the same goal by using different degrees of freedom (e.g. muscles, joints) and (b) use the same degrees of freedom to reach different movement goals. It has been suggested that organizing the degree of freedom is a major problem especially in abnormal gait patterns (Stergiou, 2004) or when the constraints of the environment are dramatically changing (Stergiou et al., 2001a). Coordination is defined mostly by the relative movements between segments of one limb (intra-segment coordination) or different limbs (inter-segment coordination). The general problem for coordinating the system has stimulated the proposition of theories (i.e. cognitive or dynamical system theories). One strong theoretical background is based on the analysis of non-linear dynamical systems. From this dynamical viewpoint, motor behaviour is considered as a system whose evolution has characteristics in common with self-organised natural physical systems (Kelso, 1995). The hypothesis being that the coordinative structure would be generated in reference with the internal and external constraints imposed on the system. With reference to the Dynamical System Theory, further qualitative and quantitative analysis techniques have been developed in motor control research.

The investigation of lower extremity actions with kinematic analysis of individual lower extremity joints (such as developed in the previous section) does not address the interaction between joints (Hamill et al., 1999). Nigg (1993) reported the need for biomechanical research to move from its descriptive phase to a more analytical level. Indeed, discrete kinematic measurements (i.e. joint angle at heel contact) and their corresponding time histories fail to capture the dynamic nature of the movement Therefore, additional analytical techniques using kinematic raw data have been developed to account for the coordination existing between segment in human movement. Segmental interactions could be examined by analysing sets of time series data obtained from adjacent body segments or joints with qualitative and quantitative analysis techniques.

The following sections aimed to present selected analytical techniques reported in the literature for the investigation of coordination.

2.3.3.1 Qualitative analysis of segment coordination

Coordination is mainly determined qualitatively by phase diagrams and angle-angle plots (e.g. of joint positions or speeds, or segment angles and angular speeds). Variable-variable plots (Schmidt and Lee, 1999) have been used extensively to analyse the motion of one joint relative to the motion of another joint (angle-angle plot) and the angle of one joint relative to the angular velocity of that joint (phase-angle plot). This technique has been useful for describing the lower limb coordination differences between a running or a galloping locomotion (Whitall and Caldwell, 1992). These techniques may be interesting, for example for describing the coupling between the upper and lower limbs in DST for comparison to running and walking, since it has been proposed that the skiing locomotion may be developing form the other two (Parks, 1986; Smith, 1990).

The analysis of coordination, using only variable-variable plots limits the scope of investigation of the researcher. Although different coordination behaviours have been reported through observation (Whitall and Caldwell, 1992), the quantification of those differences is only accessible through higher level of analysis. Therefore, the limitations of qualitative analysis of segment coordination implied the development of additional technique analyses (Stergiou, 2004).

2.3.3.2 Quantitative analysis of segment coordination.

2.3.3.2.1 Time sequencing of joint angular parameters

Different techniques have been used to quantify the inter-limb and intra-limb coordination. Time data of specific events (e.g. heel strike, maximum segment extension, or joint angular velocity peaks) in the segment constituted a first mean to account for the relationship between segments. Whitall, (1989) and Whitall and Caldwell (1992) investigated the interlimb coordination of running and galloping gaits. The temporal occurrence of maximum flexion and extension of each limb has been reported as a percentage of the cycle. Whitall, (1989) and Whitall and Caldwell (1992) reported different limbs sequencing hence leading to the concept of symmetric and asymmetric gaits. This method has further been applied for describing the segmental organisation for undertaking efficiently some sporting tasks.

Temprado et al., (1997) compared the times of maximum backward displacement of each limb segment between expert and beginner volley ball players, revealing differences in the coordination patterns. The authors revealed a proximo-distal sequencing activation of the joints. Similarly, Bobbert and Van Ingen Schenau (1988) and Rodacki et al. (2002) analysed the coordination in vertical jumping with the display of the amplitude and the time histories of angular velocity of body segments. The difference at which the peaks of angular velocity of each joint occurred in the movement was used to determine the relative timing and the sequential relationship between adjacent segments. The authors showed a proximo-distal sequencing of the lower limb joint extension phase beginning with the hip, and followed by the knee and the ankle, approximately 100 ms and 200 ms after. Additional electromyography data reinforced the kinematic observations over the sequencing of the muscle activation (Bobbert and Van Ingen Schenau, 1988).

The analysis of the sequencing of joint parameters may be useful in DST for describing the upper and lower joints coordination and their involvement in the propulsion mechanisms. Although the joint activation occurrence in the movement gave an insight on the relationship and organisation between the segments, this analysis technique did not account for the phasing relationships existing between the segments. Hence, further and more complex analyses are required.

2.3.3.2.2 Relative Phase

Developing from the phase-plot angle, the relative phase (Stergiou, 2004) constitutes a measure of the interaction or coordination of two segments during gait cycle. It developed from the hypothesis that systems auto-adjust (i.e. Dynamical System Theory) (Kelso, 1995). To calculate relative phase, the phase angle of the distal segment is subtracted from the phase angle of the proximal segment for each i^{th} data point of the time-normalised gait cycle. The uniqueness of the relative phase measure presented is that it compresses four variables (proximal and distal segments' displacement and velocities) into one measure. Incorporating velocity and displacement into one measure has an advantage over biomechanical measures as suggested by evidence in the literature that there are both displacement and velocity receptors in the joint structures (Enoka, 2002). Although criticisms have been postulated against the relative phase (Schmidt et al., 1991), Kurz and Stergiou (2002) reported it to be an efficient variable for describing the limb coordination. Much research on relative phase has investigated the coordination in human locomotion.

This quantification of the phasing relationship between objects has been very fruitful for investigating the effect specific parameters on human movement. Hamill et al. (2006) reported that this analysis has furthered the understanding of the causes of injuries in the lower limb. Relative phase analysis has challenged some established concepts regarding motor control strategies in human locomotion. For example, Nilsson et al. (1985) suggested that the kinematic and electromyographic differences present in walking and running are the consequences of fundamental differences in motor strategies between the two major forms of human progression. In contrast, Li et al. (1999) showed that the coordination patterns between the thigh and leg were similar for walking and running for most of the cycle. Therefore the authors proposed that more subtle differences in motor strategies could be reported between the thigh and leg between walking and running. Differences in the lower limb coordination between gaits occurred at the event of the toe-off. Whereas in walking the swing leg moved forward relative to the body, in running it moves backward relative to the body. The coordination between the thigh and the leg for the different part of the cycle (early support, late support and swing) showed evidence of clear functional differences between walking and running (Li et al., 1999). Unfortunately the authors did not investigate the segments relative to the ankle joint where major kinematic differences have been reported between walking and running (Nilsson et al., 1985; Mann and Hagy, 1980). The DST literature did not present enough data to relate the locomotion intra-limb coordination with walking and running.

The relative phase technique may be useful in DST, for example, for describing the influence of a change of equipment or wax on the segments coordination during the propulsion phase, since the application of force may develop from an accurate phasing relationship between the muscles of the segments (Zajac et al., 2002).

2.3.3.2.3 Cross-correlation

Another way of quantifying the degree of similarity between two sets of segmental kinematic data is by using cross-correlation (Stergiou, 2004). Cross-correlation has been used in gait or sport biomechanical studies (Temprado et al., 1997; Pohl et al., 2006). The signs of the correlation coefficients reveal the types (i.e. in-phase or anti-phase) and the strength of relationships between the joints. Different statistical techniques have been developed to cross-correlate various kinematic and kinetic data (Li and Caldwell, 1999).

To summarize section 2.3.3; although, coordination analyses provide a strong background for understanding the underlying coordinative structure used in diverse tasks in human movement; it does not allow an overall view of the mechanisms used in human locomotion to progress along the ground. Additional analytical technique is required to undertake such investigation. Mechanical paradigms (i.e. potential energy, kinetic energy) have been successfully used for various human, animal and assisted locomotion (Saibene and Minetti, 2003; Minetti, 2004).

2.3.4 Mechanical determinants of walking and running

The human spends chemically bound energy to move. Through diverse metabolic processes, the energy is transformed into mechanical work and heat. Examination of mechanical work and energy is an important field of biomechanics research. This research potentially benefits from understanding a basic law of nature: the law of conservation of energy. The complexity of the human body (i.e. a multilink system) makes the determination of the mechanical work and power a challenging task (Zatsiorsky, 2002). To understand the basic principles ruling locomotion it is preferable to refer first to the trajectory of the body centre of mass defined as the point where all the mass could be considered to concentrate. This simple approach to the mechanical study of bodies in motion cannot reveal all the determinants of movement, but the overall paradigm is easily detectable. For example the exchange among different types of energy (potential: vertical position; linear kinetic: linear speed; rotational kinetic: rotational speed) obtained by the displacement of the Body centre of mass may be characterised by simple play-ground games such as a swing, or a yo-yo. The other important energy form, not directly detectable by inspecting the body centre of mass trajectory, is the elastic energy. This derives from the capability of certain materials to deform (under compressive, tensile of bending stress) and successively recover the initial shape, storing and releasing mechanical energy in the cycle.

These three energy forms (potential, kinetic, elastic) and their interchanges are essential to the understanding of gross body movement (Saibene and Minetti, 2003). The calculations of energy fluctuations of the segments and the body centres of mass allow an overall modelling of different gaits. In humans, the mechanism for progressing can be detailed through the analysis of the two main human locomotion: walking and running.

2.3.4.1 Mechanical characterisation of walking

Walking is an economical activity, its energy requirement being only 50% above the metabolism at rest (at 0.6m/s it is about 2.44 W.kg). In contrast, running can be very demanding and can only be continued over limited time (Saibene and Minetti, 2003). The low energy demand in walking develops from the intrinsic characteristics of the locomotion that a mechanical analysis will more deeply detail.

2.3.4.1.1 Walking as a pendulum

During the walking cycle (figure 2.20), the body centre of mass rises between stages 1 and 2 but the body centre of mass also slows down. Then, the body centre of mass falls and speeds up between stage 2 and 3. Therefore, some mechanical energy fluctuation (i.e. potential and kinetic energies) of the body centre of mass takes place. Mechanical energy appears to be swapped back and forth between potential energy (E_P) and kinetic energy (E_K) but the total (kinetic plus potential) remains constant (Cavagna et al, 1963) (figure 2.20). In other words, E_P and E_K follow an out of phase relationship. Thus, economy in walking is maintained by the effective interchange between potential and kinetic energy of the body centre of mass, rather than the one of the legs.

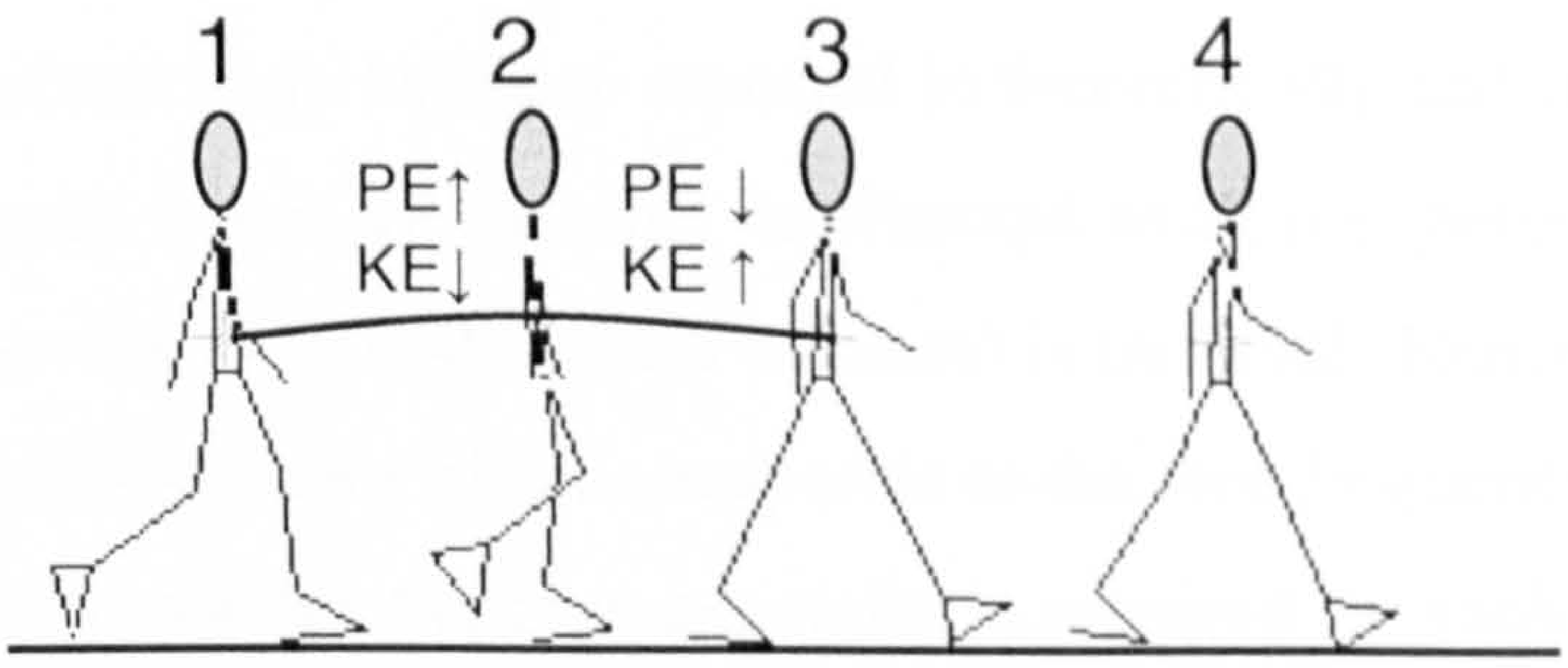


Figure 2.20: Walking. PE =Potential Energy; KE=Kinetic energy (adapted from Alexander, 1992a); PE =mgh and KE = 0.5 mv^2 where m, g and v represents the mass of the subject, the gravitational force (9.81m/s^2) and the velocity of body centre of mass respectively.

From this observation, a walking person has been modelled as a swinging pendulum (Margaria, 1976), so the muscles need to do very little work to keep the walker moving, explaining the low metabolic cost of the locomotion (Cavagna et al., 1963, 1976; Cavagna and Margaria, 1966). This has been confirmed by the observation of rather small muscles activities (Basmajian, 1979). In addition, similar conclusions were made by Mochon and McMahon (1980) relative to the swing phase of free walking. They reported that the foot during the swing phase was similar to a purely ballistic model without muscular contraction.

The quality of the exchange between potential and kinetic energy can be estimated by the well-known ratio developed by Cavagna et al. (1976). The percentage of energy recovery (equation 2.3) gives the amount of transfer between work done by gravity (Wv), and work done in accelerating forwards (Wf) and vice versa.

Equation 2.3: $$\left[\left(W_f + W_v - W_{ext}\right)/\left(W_f + W_v\right)\right] * 100$$

where W_f is the work in accelerating forward the body centre of mass, W_v is the work against gravity and W_{ext} is the total work generated to raise and accelerate the body centre of mass within the environment.

The percentage of recovery has been reported close to 65 at intermediate speeds of walking (Minetti and Saibene, 1992). If the human body were an ideal pendulum 100% energy recovery would be obtained. Minetti and Sabeine's result suggested that some loss and addition of energy was observable in walking. Cavagna et al., (1977) showed that the event of the foot contact is the main source for the loss of energy. Additional energy may be generated through propulsion forces.

In walking, the human body has been reported to theoretically and empirically have an optimal frequency where the external mechanical work (i.e. potential and kinetic energy required to move the body centre of mass) is minimal (Minetti and Saibene, 1992). This optimal frequency also corresponds to the step frequency people naturally choose with the least energy expenditure required for each constant speed (Elftman, 1966; Minetti et al., 1995). These observations validate the modelling of walking as a pendulum. In walking, the body centre of mass rotates about its support (figure 2.20) with its mechanically determined own natural frequency. Thus, the optimal frequency generating the least energy expenditure is dependent on the natural frequency of the body during walking. The optimal stride frequency of the system is clearly dependent on the height of the subjects, such an increase in subject height results in lower optimal stride frequency (Brenière and Do, 1991). Either above or below the optimal stride frequency, the mechanical work and the energy expenditure have been reported to increase (Minetti et al., 1995) (figure 2.21).

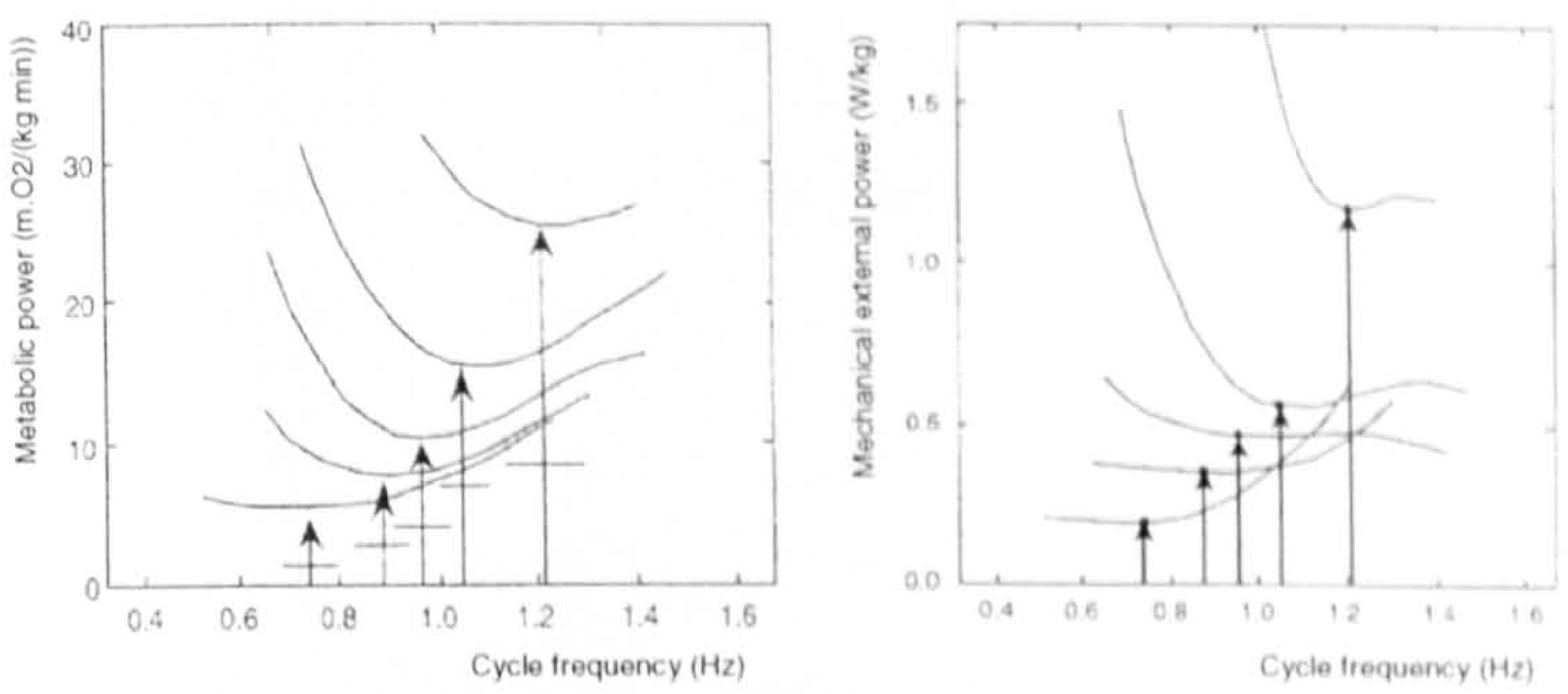


Figure 2.21: Metabolic power (left) and mechanical external power as functions of stride frequency. Walking speeds evolved from 0.69 (lowest curve) to 2.08 m.s-1(highest curve). Arrows correspond to the cycle frequency freely chosen (from Minetti et al., 1995)

Cavagna and Franzetti (1986), Minetti et al., (1995) investigated the mechanical reasons for this increase of energy expenditure in walking while increasing or decreasing the step frequency at a constant velocity. In their model, walking was not modelled as a pendulum; rather the authors modelled the loss of energy in walking with the angulation of the leg at foot contact. For this purpose, the work done to move the body centre of mass relative to the environment (called external work), as well as the work done to move the limbs with respect to the body (called internal work) were both included in the model. As a result, the reasons for a greater mechanical work when the cycle frequency is lower for the same speed have been suggested. The hypothesis was that the maintenance of the given speed with longer steps at a lower frequency increases the braking effect of heel strike. Thus the body is decelerated to a greater extent and then must be accelerated more to restore the lost of energy. This assumption was supported by the observation of larger anterior-posterior braking and propulsive ground reaction force with increasing step length (Keller et al., 1996). This has to increase the external work performed. Therefore, the foot plantarflexion during the late stance phase has an important effect in walking for covering the loss of energy induced by the brake at foot touch. Furthermore, the foot plantarflexion raised the centre of gravity a little higher, smoothing the gait transition by raising the body centre of mass (increasing the radius of rotation) before the foot contact. As a consequence, the action of the foot smoothes the transition between steps.

2.3.4.1.2 Simple model for walking

Walking is a quite an economical locomotion to progress on the ground at slow speeds. However the gait becomes uneconomic at high speed (Minetti et al., 1995). Furthermore, walking is limited to a maximum speed; to go faster humans have to change their gait to running (Alexander, 1992a).The limitation in walking speed has been explained using simple mechanical model (Alexander, 1991a, 1992a,b). As a body moving in a circle has acceleration towards the centre; the centripetal acceleration. If the speed of the trunk is v this acceleration is v^2/r. At the stage of the stride when the leg is vertical, this acceleration is directed vertically downwards. It cannot be greater than g, the acceleration of a body falling freely under gravity:

Equation 2.4: $v^2 / r \leq g$,

$v \leq (gr)^{1/2}$.

This inequality (equation 2.4) sets a speed limit for walking. On earth, g is about 10 $m \cdot s^{-2}$. Normal adults have leg lengths r of about 0.9 m, so the inequality tells us that we cannot walk faster than $((10 \times 0.9)^{1/2} = 3$ $m \cdot s^{-1}$. This is a little faster than the speed at which subject spontaneously start running but slightly lower than their maximum possible walking speed. The later observation may possible being due to the role of the knee; with knee flexion at midstance serving to flatten he trajectory of the centre of mass and effectively increasing the radius of rotation. In walking races, athletes can reach higher speeds by changing the movements of the hip increasing the effective length of the leg further

2.3.4.2 Mechanical characterisation of running

Running presents completely different mechanical patterns than the ones in walking (figure 2.22). Observation of the running motion shows that the body centre of mass slows down at stages 2 and speed up at stage 3. Thus the body travels slower at stage 2 and faster at stage 4. Also in running, the body centre of mass is low at 2 and high at 4. Thus the potential energy and kinetic energy are both high at 4 and low at 2, so the pendulum principle that we saw operating in walking cannot work in running (figure 2.22). In other words, PE and KE follow an in-phase relationship. The percentage of recovery, indicating an energy exchange with a pendulum-like pattern has been reported close to zero and independent of speed (Cavagna et al., 1976). It has been shown that much of the kinetic energy that is lost and regained in the course of a step is stored up as elastic strain energy in stretched tendons and ligaments and returned in elastic recoil. Therefore, running is not like a pendulum, but considered to be more like a bouncing ball or a pogo-stick (Margaria, 1976; Cavagna and Kaneko, 1977; Blickhan, 1989; Alexander, 1992a).

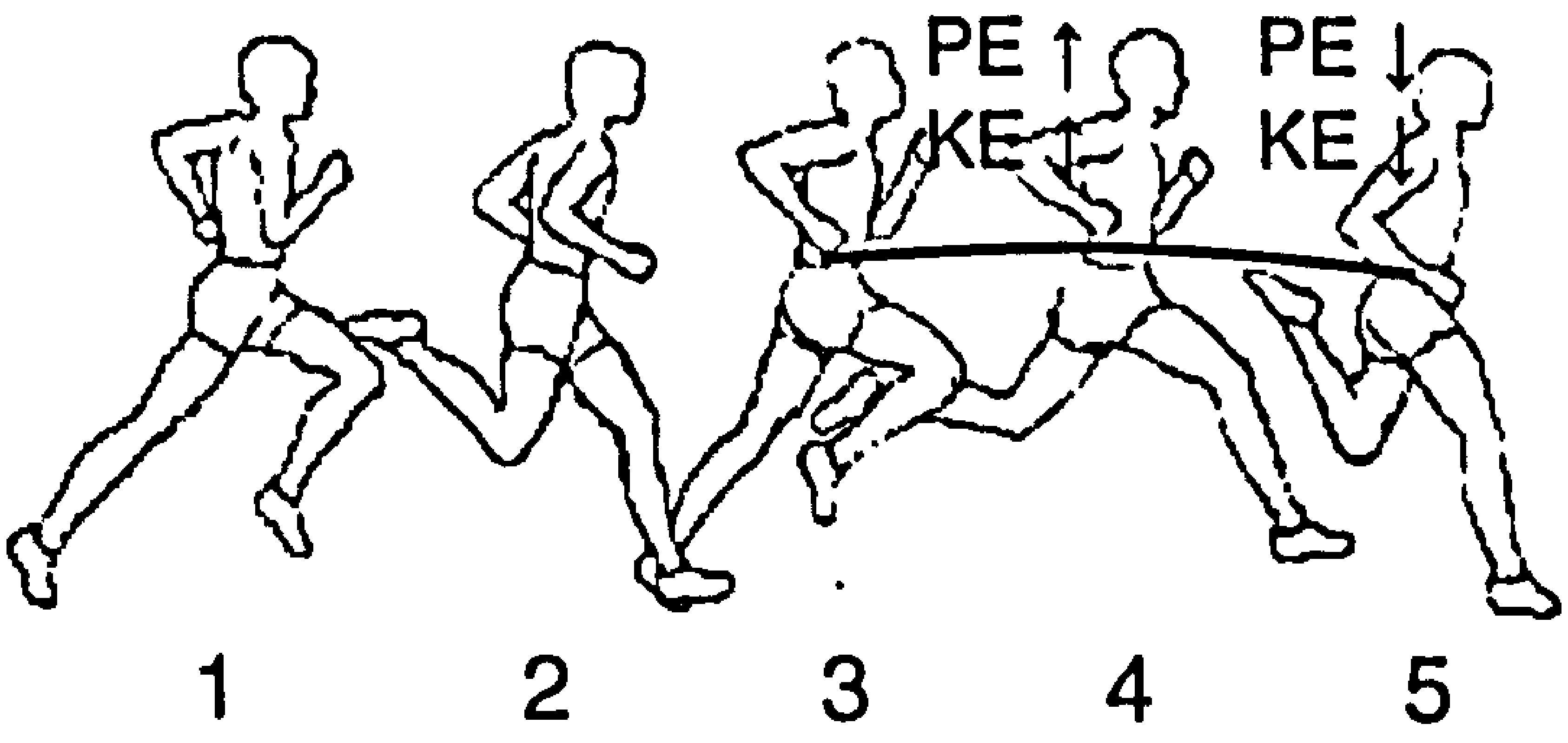


Figure 2.22: Running. PE: Potential Energy; KE: Kinetic Energy (adapted from Alexander, 1992a) PE =mgh and KE = 0.5 mv^2 where m, g and v represents the mass of the subject, the gravitational force (9.81m/s^2) and the velocity of body centre of mass respectively.

One way of understanding and estimating the proportion of stretch-recoil of elastic energy in the lower limbs in locomotion may be done with the concept of muscle efficiency. The maximal efficiency of the transportation of chemical energy into positive mechanical work (i.e. work needed to move the body centre of mass) by muscles is about 0.25 for the whole human being (Woledge et al., 1985). The efficiency of locomotion is calculated as the total mechanical work, Wtot (i.e. sum of internal and external mechanical work) divided by the net energy expenditure (i.e. metabolic cost minus the resting metabolic cost) (Cavagna and Kaneko, 1977; Winter, 1990).

The overall efficiency of the positive work done during locomotion, gives an indication of the relative importance of the contractile versus the elastic behaviour of muscles. In fact a value greater than 0.25 indicates that part of the positive work is delivered, free of cost, by an elastic element stretched by some external force during the prior phase of negative work (i.e. work done by gravity on the body centre of mass). Cavagna et al. (1964) and Cavagna and Kaneko (1977) measured the efficiency during level walking and running at different speeds (figure 2.23). Cavagna and Kaneko (1977) reported efficiency values in running as high as 0.8, indicating that the stretch-shortening cycle is a highly profitable process.

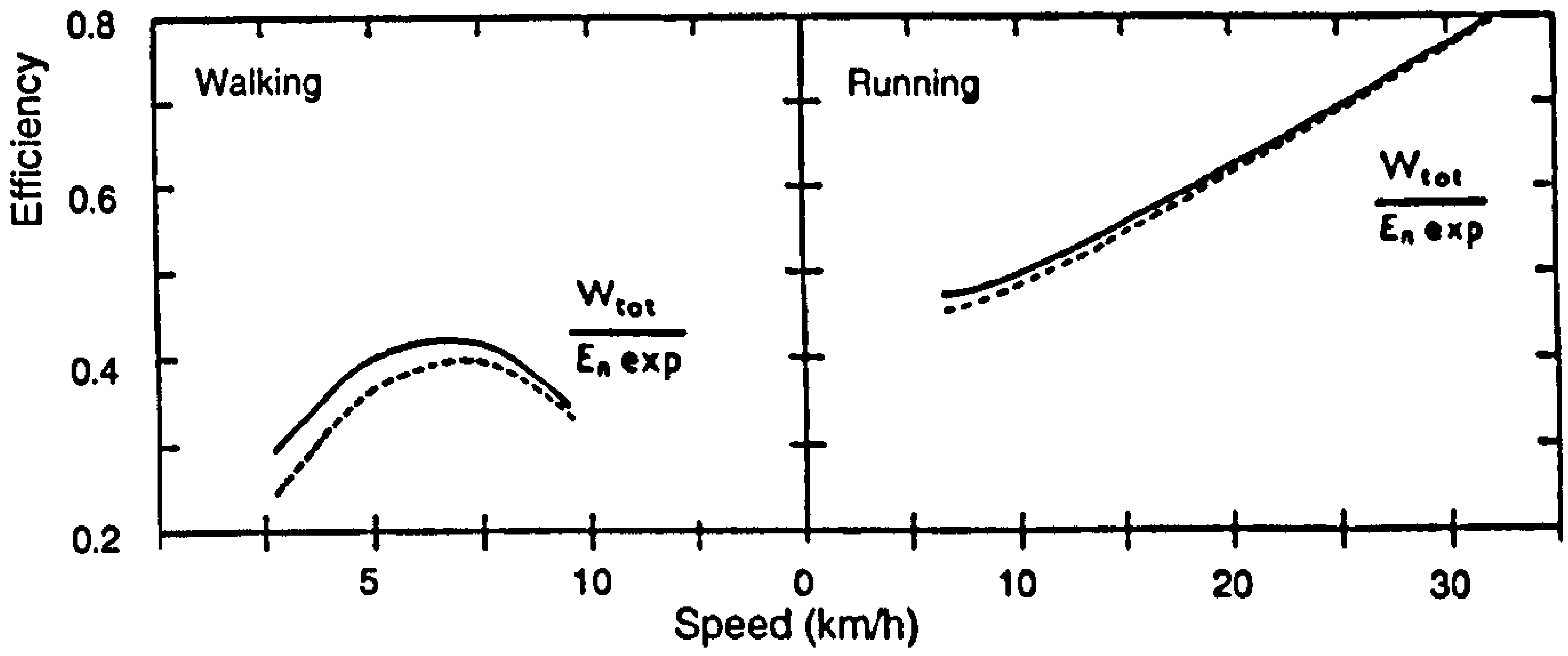


Figure 2.23: Efficiency versus speed in walking and running. (from Cavagna and Kaneko, 1977)

Same authors reported that efficiency was greater in running than in walking. This observation is in agreement with the different energy exchange of the two gaits (i.e. in walking potential and kinetic energy of the body interchange (as a pendulum) whereas in running they both enter in the muscles to be restored immediately during subsequent shortening). It is proposed that in walking the forces involved are too weak to stretch the tendons appreciably to store elastic energy. As observed in the above figure, the efficiency changes with the speed of locomotion. In running, the efficiency increases continuously with speed. Thus the role played by elasticity prevails over that of the contractile machinery.

2.3.4.2.1 Structures underlying the process of storage and release of energy in running

In running, different components of the lower limb take part in the storage of elastic energy. The muscle fibres can stretch elastically but at most only 3% of their length. The most important spring in a leg is not the muscle but the tendon. The quadriceps muscle has the tendon in which the kneecap is embedded, and gastrocnemius and soleus attached to the heel by the Achilles tendon. It has been shown that tendons can stretch up to 8% without breaking, and recoil elastically.

In addition, tendons represent very good springs, being tested to return about 93% of the work done to stretch them (figure 2.24). Therefore tendon is as good as most rubber, though not as good as steel springs (Bennett et al., 1986; Alexander, 1977, 1988). Three different locations in the leg have been reported to act as a spring in the lower limb during running.

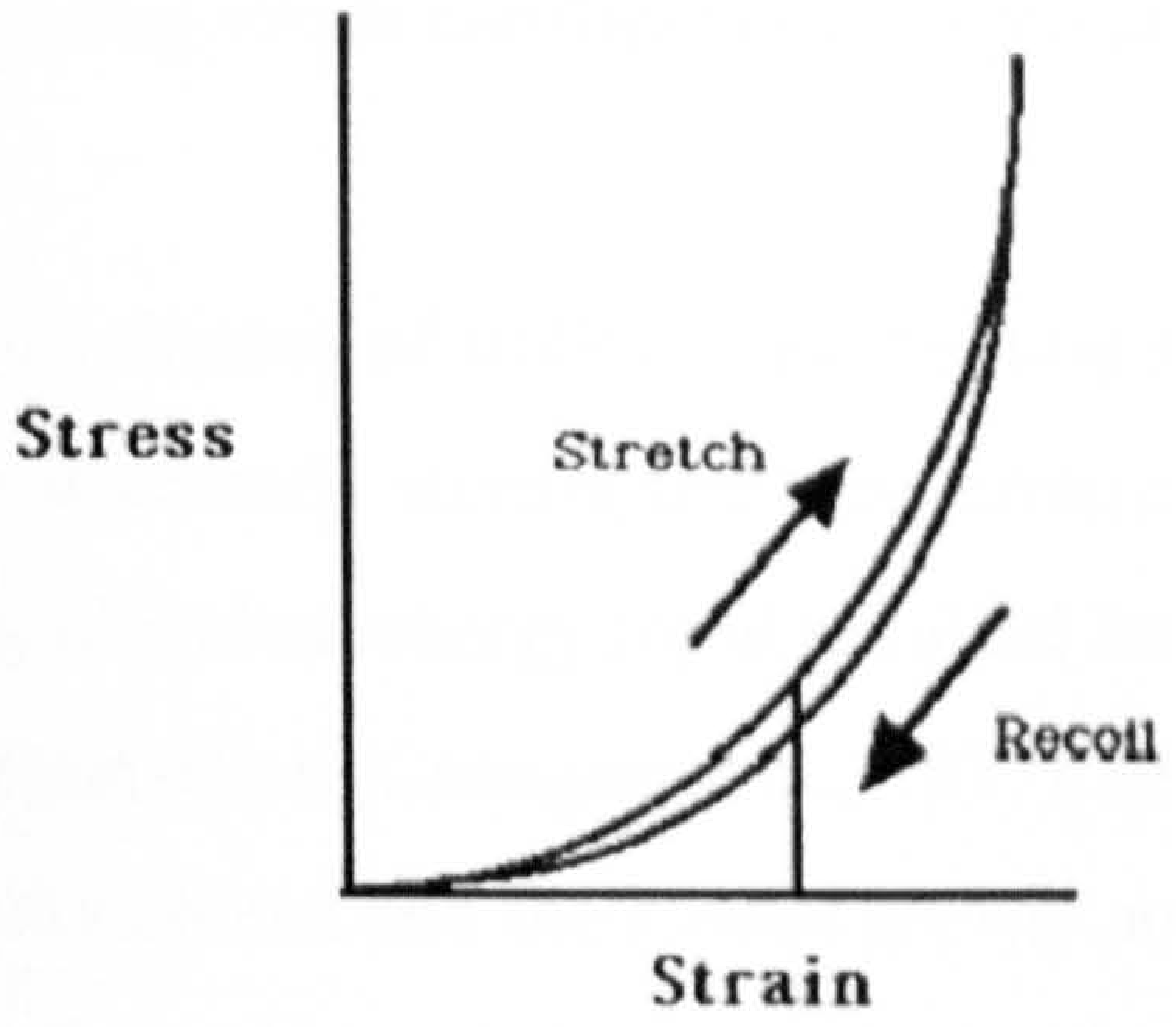


Figure 2.24: Energy lost by the tendon after being stretch. Tendons efficiently recoil in a spring like fashion returning approximately 93% of the energy stored when stretched (from Novachek, 1998)

The quadriceps (muscle and tendon) play an important role in the storage and recoil of elastic energy during the cycle. Then, the Achilles tendon constitutes another very important spring responsible for the ankle movement while the runner's foot is on the ground (Ker et al., 1987). The foot arch, maintained by ligaments, also acts as a spring but 20% of the energy was found by Ker at al. (1987) to be lost as heat: The foot is not as good a spring as the tendons. The stretching of the tendons and the deformation of the arch prevents the muscle from lengthening and shortening as much as they would otherwise, and also from shortening as fast. This constitutes an important advantage since the release of energy added to the concentric action of the muscle during the second part of the stance phase will enhance the performance. This has been demonstrated on isolated muscle preparations with constant electric stimulation (Bennett et al., 1986) and in animal locomotion with natural and variable muscle activation (Alexander, 1988; Minetti et al., 1999). As with many other movement repertoires (counter-jump, throwing and cross-country skiing), running involves muscle action in which the concentric phase is immediately preceded by an eccentric phase (pre-stretch). In running this muscle action has been referred as the stretch-shortening cycle (SSC) (Komi and Bosco, 1978; Komi and Norman, 1987; Komi, 2000) and can be kinematically and electromyographically observed in the locomotion.

Running locomotion uses the properties of the muscle to make metabolic savings and absorbs the shocks related to the large amount of force generated at foot strike. The provision of additional spring such as one from a floor with using sprung wooden beams has been reported to augment by 3% the running performance (Mc Mahon and

Greene, 1978). This interesting result confirmed the implication of the spring elements in running.

The consideration of the mechanics of walking and running shows that there are two different mechanisms for alternately storing and recovering energy. These mechanisms minimise the chemical energy input required for performing the external work require in human locomotion (Cavagna et al., 1977). In walking, there is an exchange between the gravitational and the kinetic energy, as it occurs in a swinging pendulum but in running the exchange is between the mechanical energy stored in muscles' elastic elements and both the kinetic and gravitational energy. If the economical aspect is so primordial, a similar kind of energy exchange should be reported in additional locomotion and quadrupedal gaits. The following paragraph details the energy fluctuations observed in skipping, and animal trotting and galloping. This may contribute to the development of our understanding of the way humans and animals move and save energy.

2.3.4.3 Energy saving mechanisms in human and animal locomotion

Bipedal walking and running in humans, walking in birds, quadrupedal walking, trotting, galloping, hopping can all be reduced to two general mechanisms, a pendulum and a spring, which have been utilized either singly or in combination to minimise the expenditure of chemical energy by the muscles for lifting and reaccelerating the centre of mass within each stride (Cavagna et al. 1977). The same authors reported that walking in animals is essentially the same as that described for man with a transfer of E_P and E_K in the body centre of mass. Similarly, human running and animal galloping use the same mechanisms for storing-releasing energy (i.e. exchange between mechanical energy stored in the muscles' elastic elements and recovered as both kinetic and gravitational). Therefore, a walking animals gait can be imitated by two humans walking one in front of the other, and walking 75% out of phase. Similarly, an animal trotting would correspond to two humans running 50% out of phase (Minetti, 1998) (figure 2.25).

The animal galloping constitutes a more complex locomotion since researchers observed the utilisation of the two energy-saving mechanisms (Cavagna and Margaria, 1963; Alexander, 1988, 1991c) that were operating simultaneously. This observation was based on the fact that the elevation of the body centre of mass increased with increasing velocity in galloping as in trotting. However, the energy recovery parameter is higher during galloping than during trotting, showing greater pendulum-like limb movement (Cavagna et al., 1977; Minetti et al., 1999).

In humans, the utilisation of both energy transfer mechanism can be also observed in skipping (i.e. a gait children display at about 4.5 years old). Skipping differs from walking by presenting a significant flight phase, but also differs from running by having a double support period. In addition, its time-courses of the potential and kinetic energies of the body centre of mass resemble an intermediate pattern with respect to walking and running. As in walking, the forward kinetic energy and the potential energy are partly out of phase. From the mechanical energy patterns, skipping and galloping in quadrupeds are related. Thus, galloping at low speed can be imitated by two humans performing unilateral skipping with 25% of the stride period being out of phase. At higher speeds the only difference would be the phase between the two humans, which would approach 50% and include a second flight period (Minetti, 1998). Therefore in skipping as in galloping the two basic energy savings mechanisms (i.e. the potential-kinetic energy inter-change and the elastic storage-release) seem to be simultaneously operating. These mechanisms are confirmed by intermediate values of energy recovery (Cavagna et al., 1977; Minetti, 1998) (figure 2.25).

From these observations of the mechanical energy patterns it can be proposed that the pogo stick is a convenient simplification for running, trotting and hopping, whereas galloping and skipping are better represented by a rimless wheel with springy spokes.

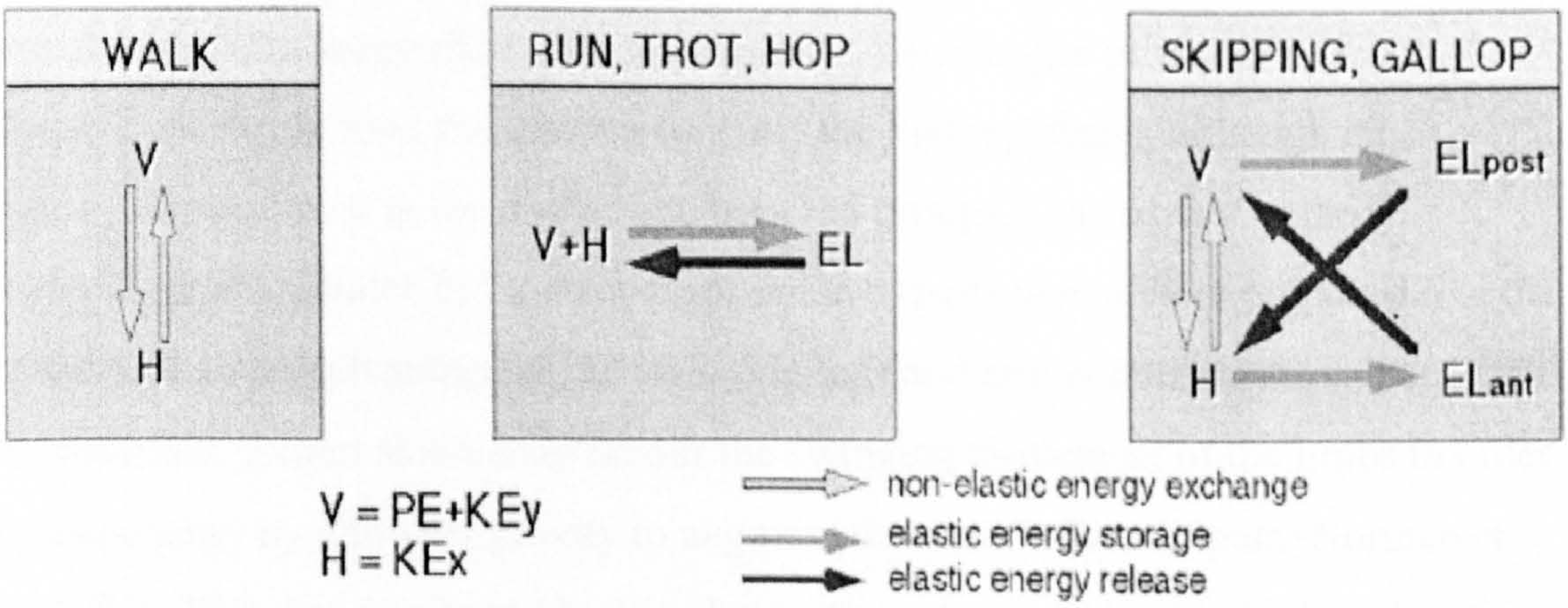


Figure 2.25: Mechanical energy flow during ground contact in bipedal and quadrupedal gaits (from Saibene and Minetti, 2003)

In addition, skipping is metabolically more demanding than running at the same speed, whereas horse galloping shows the same cost of transport as trotting. The reason why the same mechanical principle is associated with such different metabolic energy expenditures probably lies in the number of limbs and in the type and amount of elastic structures involved: In quadrupeds, longer limb ligament and spine ligament can be seen.

Mechanical calculations provide an effective tool for understanding and discriminating human or animal locomotions. This kind of analyses can be hugely interesting for characterising the DST locomotion, and allowing a comparison with other gaits. Since two energy-saving mechanisms have been observed in walking and running, one can ask which one is the most representative of the DST locomotion.

2.3.4.4 Mechanical analysis in the DST

A number of studies have undertaken mechanical analysis of the DST with the purpose of discriminating different performance level skiers (Norman et al. 1985, 1989; Norman and Komi, 1987). Norman and Komi (1987) reported that the overall mechanical work rate of the faster skiers were somewhat larger than those of the slower group in both level and uphill conditions. Norman et al (1985) calculated the amount of energy transferred between and within (transfer between potential and kinetic energy) body segments. The calculations of mechanical energy output and mechanical energy transfer were conducted using the method described by Pierrynowski et al. (1980). The total body and between-segment transfers were not statistically different between recreational and elite skiers. However, expert skiers had significantly higher within-segment transfers than novices. They exhibited greater potential energy (E_P)/ kinetic energy (E_K) exchanges primarily in the segment: swinging foot, the kicking foot and the kicking shank, although all 11 segments contributed to the distinction between groups. Consequent to the observation of a greater E_P/E_K exchanger in the experts, the authors proposed that the expert took better advantage of the swinging legs and arm pendulum movement than the unskilled. Expert skiers may favour the swinging movement of the limbs in order to save energy by allowing gravity to augment the muscle force inputs (Norman et al., 1985). This was confirmed by the observation of a considerable higher elevation of the leg at the beginning of the recovery phase in expert skiers (Dillman et al., 1979). Consequent to these strategies for saving energy, the mechanical task cost (i.e. mechanical work required to move one kilo of body mass one meter) has been reported lower in faster skiers than in slower skier on flat and uphill terrain (Norman and Komi, 1987). Overall, under uphill conditions, the mechanical power output presumed to be the result of greater muscular output was higher for the faster finishing skiers, enabling them to ski faster on the uphill (Norman et al., 1989). However, authors highlighted the variability existing in the percentage of mechanical energy transferred between the skiers. Therefore, Norman and Komi (1987) pointed out that whereas these studies gave some true insights on the mechanics of elite cross-country skiers, final differences within subjects can be the result of errors in the measurement and calculation of mechanical energies.

In the DST literature, the mechanical role of the swinging leg has been largely studied with an evaluation of the energy transferred to the rest of the body. However, the overall mechanics of the body centre of mass has not been studied and so very little information regarding the propelling mechanisms and energy-saving system used in the DST exist.

Section 2.3.4, reviewed the mechanical paradigms used by human and animal to progress along the ground. The investigation of mechanical energy exchange within the body centre of mass reported two main energy-saving mechanisms in locomotion (i.e the potential-kinetic energy interchange and the elastic storage-release). In the DST, it is supposed that the same mechanisms would be acting. However, this hypothesis needs to be based on further analyses which may help understanding how skiers progress along the ground

2.3.5 Summary

Numerous analytical techniques have been used for the study of human movement; qualitative and phases analyses constitutes a first level of analysis for characterising differences between human locomotions. Joint angular analysis allows a description of the role of joints in the locomotor patterns. Coordination analyses aims to develop an understanding of the relationship existing between body segments for the successful completion of locomotor tasks. Finally mechanical analysis provides an overall view of the energy exchange occurring within the body centre of mass, hence a mean to describe the overall mechanism for progressing along the ground. Each analytical technique provides different type of information to help our understanding of the biomechanical mechanisms used by human to perform a specific task.

The literature on walking and running provided a strong background for the understanding of the strategies developed by humans for progressing along the ground. In contrast, the poor amount of information on the DST limits our comprehension of the locomotion. Therefore, additional knowledge is required.

2.4 Modifications of locomotor patterns with the environment and materials

The consideration of the DST as an extension of walking and running exhibited the importance of reviewing the impact of a gliding environment and of the use of external material onto walking and running locomotor patterns. A hypothesis may be that similar strategies could be used in DST as in perturbed walking and running. Therefore, this section will describe the locomotor adaptation of walking or running under related environmental and material conditions; i.e. the change in the biomechanics of walking while experiencing some gliding perturbation in the cycle, and the effect of additional materials on the biomechanics of walking and running.

2.4.1 Biomechanical strategies in walking under slippery ground

Falling after a slip in walking represents an important cause of injuries in the population. Slip and fall accidents raise particular ergonomic concerns (Cham and Redfern, 2002). Therefore, the locomotor adaptation of humans to perturbation has been fully investigated with kinematic and kinetic studies (Patla, 1993; Pai and Iqbal, 1999; Grönqvist et al., 2001; Smeester et al., 2001; You et al., 2001; Cham and Redfern, 2002; Marigold et al., 2003). In walking the most hazardous phase for slip is the period of time shortly after the heel strike (double support phase) when the centre of mass moves from behind to ahead of the base of support (Patla, 1993). The double support phase represents a critical phase for recovering balance and thus is temporally increased with the slippery perturbation.

2.4.1.1 Protective gait strategies

Following a slip, the main strategy to keep balance is to position the body centre of mass over the base of support so that the projection of the body's centre of mass (BCM) falls into the boundaries of stability. Pai and Iqbal (1999) suggested that the control of body centre of mass displacement-velocity relative to the base of support produce good results for maintenance of stability during slipping. The balance strategies sought are directly dependent on the ability to anticipate the postural demands in response to external perturbations.

To achieve this goal, humans typically adopt a protective gait strategy, which involves the combined effect of force and postural changes of the early stance. Based on the timing relative to the event of perturbation, the adjustments can be arbitrarily classified into two postural control systems, adaptation and anticipation. Adaptation is reactive in nature and involves the co-ordination of the neuromusculoskeletal system, while anticipation is proactive and entails navigating through complex and often cluttered environments by using multiple inputs to assist in the control and adaptation of gait. It appears that subjects have the ability to adopt a wide spectrum of corrective strategies. The magnitude of the adaptation results from different conditions; either the adoption by the subjects of initial postural conditions at the onset of the perturbation or the characteristics of ground reaction forces at the shoe-floor interface (Cordero et al., 2003). The response amplitudes have been proposed to be proportional to the amplitude of the perturbation (Oddsson et al., 2004).

2.4.1.2 Limb movements

Step length and step frequency appeared to be significantly affected by a slippery perturbation while walking (You et al. 2001). As an anticipatory strategy, Redfern et al. (2001) have observed that the subject took shorter steps while entering a slippery area. Step length has theoretically an important impact on slip potential (Redfern et al. 2001). As the step length is decreased the ratio of shear to normal forces at heel contact would change, resulting in a greater shear during the initial portion of the step. Thus reducing step length is one method that can reduce the slip potential when walking. Cham and Redfern (2002) reported that shorter step in anticipating the slippery surface is coupled with a significant decrease of the foot-ramp (i.e. dorsiflexion of the ankle) and a reduction of the foot angular velocity at heel strike.

Similarly, the slip subjects modify their step length by quickly landing the foot in order to get a better true contact between the shoe and the underfoot surface, which can result in an increased grip and traction and thus a lesser risk for slipping and falling (Grönqvist et al., 2001). In addition, the contralateral toe-off and heel strike were respectively delayed and happened sooner during the cycle (You et al. 2001).

The reaction strategy of the subjects' slipping has been investigated through the kinematics of the perturbed limb (Grönqvist et al., 2001;Cham and Redfern, 2002).

To successfully overcome the slip perturbation, the response of the body needs to occur during the time interval 25% - 45% of the stance phase (Cham and Redfern, 2001). During the early stance (soon after the heel strike), Llewellyn and Nevola (1992) observed an increase of the knee flexion, which reduces the vertical acceleration and the forward velocity of the body. The increase of the knee flexion allows the subject to rotate the shank forward, restoring the ankle angle in order to bring the foot back near the body. Cham and Redfern (2001) reported that the increased flexion knee is coupled with a hip moment that has an extensor activity. The same authors identified the knee flexion/ hip extension as the most dominant response to slip responsible for the generation of corrective reactions.

By mid-stance (flat foot), the recovery attempt resulted in knee flexion values on average larger by 20° compared to dry conditions (Llewellyn and Nevola, 1992). In addition, Cham and Redfern (2001) showed that under reactive condition, by the end of the first third of the stance phase on slippery floors, shank rotations were reduced, sending the ankle into plantarflexion and the knee into flexion. Whereas the knee was involved in the recovery from a slip, the ankle appeared to play a less active role.

Several authors went further, considering the importance of the trailing leg and upper body in the gait recovery while walking.

Marigold and Patla (2002) highlighted the possible contribution of arm elevation in the occurrence of an unexpected slip. After the first unexpected slip the arms were rapidly elevated forward and outward in order to stabilize the backward displaced BCM (Marigold et al., 2003). This strategy has been already demonstrated in older and younger subjects (Tang et al., 1998). Marigold and Patla, (2002) reported that the forward and outward movement of the arm displaced anteriorly the BCM, thus counteracting its backward position relative to the support resulting from the slip. The arm responses were modulated depending on the magnitude of the perturbation. In addition, Marigold et al. (2003) showed that subjects utilize an extensor strategy for the unperturbed limb therefore the knee and hip is extended and the limb lowered to the ground (frequent use of toe touch response). This toe touch response provides complementally security to the individual by increasing the base of support (increase stability). Marigold et al. (2003) reported that the perturbed lower limb flexion was combined with the arm elevation and the unperturbed limb hip extension. The authors pointed out that these segmental adjustments would represent a dynamical multi-limb coordinated strategy for dynamic stability. The authors proposed that the CNS chooses to coordinate bilateral upper and lower limbs to stabilize the disturbed BCM and ensure safe forward progression off the slippery surface (triggering propriospinal signals within the spinal cord). With practice, the authors reported a surfing strategy. This strategy consists in holding the arms forward and outward slightly while the unperturbed limb delays landing and the perturbed limb slides on the rollers rather than stepping off quickly (figure 2.26).

The summary of the body movements observed after a slip is displayed in the table 2.7.

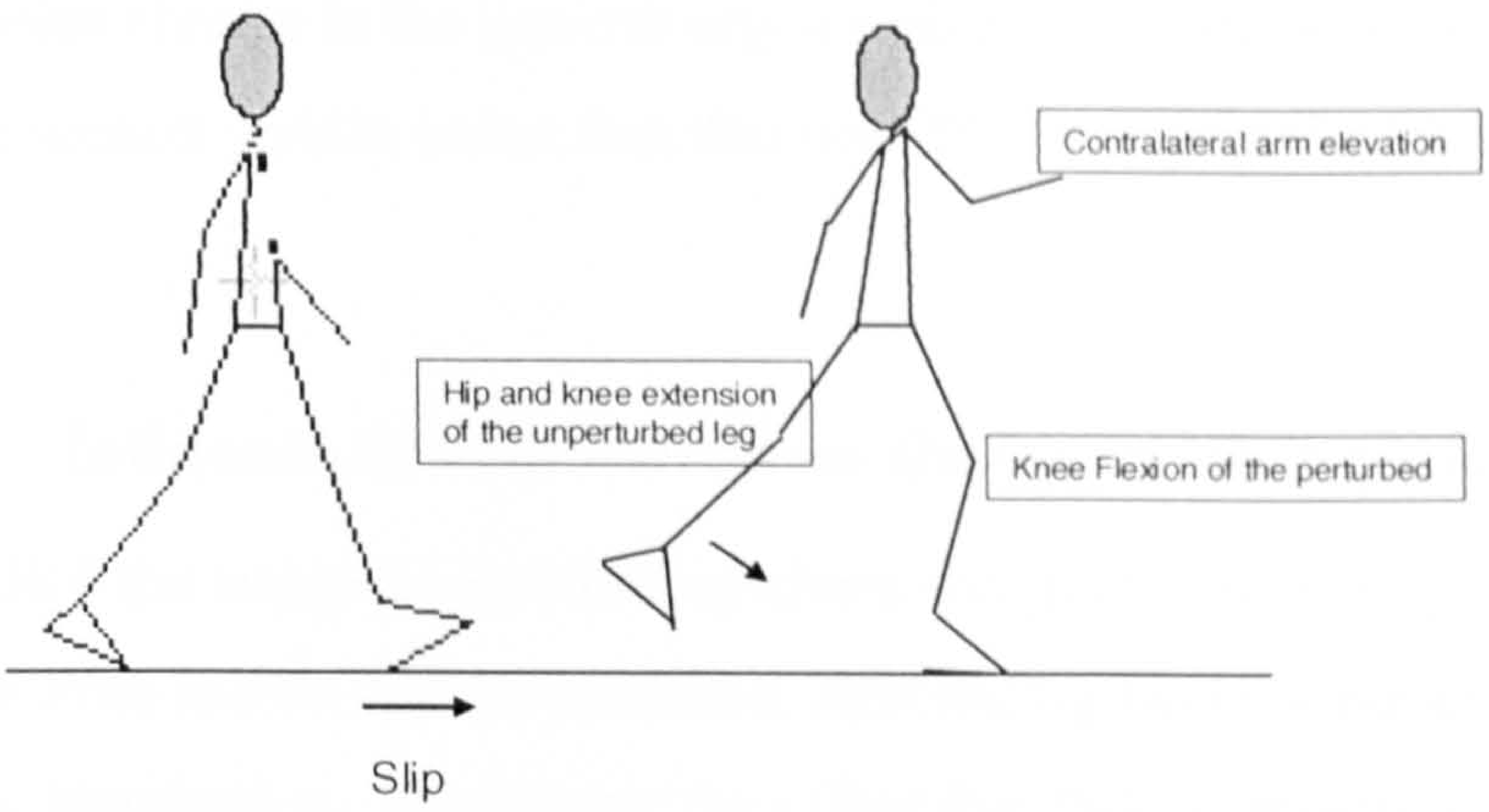


Figure 2.26: Upper and lower limb strategies for recovering from a slip while walking (surfing strategy). Illustration made from data reported by Marigold et al., 2003

Table 2.7: Recapitulation of the body movements observed after a slip.

	Movement	**Effects**	**Function**
Perturbed leg	Knee flexion Hip extension	Decrease the vertical acceleration of the body Decrease the forward velocity of the body	Allowing the shank to rotate forward in order to bring the foot under the body.
Unperturbed leg	Hip extension Knee extension	Limb lowered to the ground	Increasing the base of support
Arm	Arm elevation	Move the BCM forward	Bringing the BCM forward

The literature showed specific strategies to anticipate and react from a gliding environment. One can ask that if in the DST, although the environment presents constant slippery characteristic and the material is highly integrated to the locomotion, whether skiers use similar kinds of segmental strategies.

2.4.2 Effect of additional materials on the locomotion patterns

The previous section reported the locomotor adaptation of subjects encountering a specific type of environmental perturbation. However, it can be proposed that other environmental or material changes may affect the segmental organisation in the gait. For instance, the weight of some shoes or the weight of some prosthetic limbs may to some extent modify the inertial properties of the limb (i.e. resistance of the body to a change of magnitude of angular velocity). Additional supports using poles may also produce some major change in the general organisation of locomotion. The relevance of this section resides in the fact that the DST is practised with skis and poles.

2.4.2.1 Influence of limb inertia on the locomotion patterns

Because in the DST the complex ski-binding-shoes weigh at least 1.5 kg, it can be expected that the limb inertia will be modified, influencing the kinematics and mechanics of the locomotion. To estimate the effect that this equipment could produce on the DST locomotion, it may be interesting to estimate the increase of limb inertia on classical gaits such walking and running. Much research has been undertaken on walking and running with modification of the limb inertia (Myers and Steudel, 1985). In walking, a means of analysing the limb inertia has been to test different types of shank prostheses in comparison to normal walking patterns (Tsai and Mansour, 1986; Selles et al., 1999). In running, the change of limb inertia has been investigated to document the effect of the weight of the running shoes (Frederick, 1985; Myers and Steudel, 1985).

Numerous studies reported that the kinematics of walking were more affected by a diminution of the limb inertia rather than an increase of the limb inertia (Tsai and Mansour, 1986; Mena et al., 1999). Tsai and Mansour (1986) reported that inertial loading had a strong influence on the swing phase of prosthetic gait and that lightweight prostheses resulted in greater deviation from normal kinematics than more heavy weight designs. Mena et al. (1999) reported that the reduction of the body segmental inertial properties by 20 % had more impact on the angular deviation of the swing phase than an increase of 30 % of the body segmental inertial properties. The effect of decreasing limb inertia was observed on the shank angulation at the terminal swing and on the foot for a dorsiflexion deviation. Whereas increasing the limb inertia by 30% generated little change in the hip and knee joints compared to normal patterns, the deviation of the ankle was important. An increase of 160 % of the limb inertia may lead to an extension of the knee and an increased plantarflexion of the foot. In addition, a change of limb inertia would influence the mechanics of walking (Dillingham et al., 1992; Van Soest et al., 2001; Selles et al., 1999).

With lightweight prosthesis less kinetic energy during the swing phase can be fed back into the body. Van Soest et al. (2001) reported that changing inertial properties not only affects the pendular behaviour of the system but also affects the torque needed to correct the pendular trajectory. Thus, lightweight prostheses may require lower joint torques to control the swing phase (Selles et al., 2003). In contrast, an increase of the limb inertia may during the swing phase increase the amount of kinetic energy transfer to the body, but increasing the energy required for initiating and terminating the limb swing movement. In addition adding mass proximally to the prosthesis resulted in more normal kinematics than distally added mass (Dillingham et al., 1992).

In running, Dellanini et al. (2003) reported that limb inertial (by 6.9 % in the shank and 1.5% in the thigh) changes would decrease the maximum cycling and running movement velocity capability by at least 2.0 % and 3.3% respectively and increase the internal work associated with moderate submaximum cycling and running movements by at least 2.9 and 3.0 % respectively. The mechanical change associated with the increase of the limb inertia will have an important impact on the total work done during the stride.

This resulted in a significant increase in the energy expenditure during movement (Williams and Cavanagh, 1983; Frederick, 1985; Myers and Steudel, 1985; Chang et al., 2000). Myers and Steudel (1985) reported that the location of the load near the body' s centre of mass resulted in a significantly lower increase of the energy consumption than when the same mass was located along the limb. Williams and Cavanagh (1983) proposed that transporting added weight at the end of the leg was quite a different mode of doing work than the summary movements of all segments, and perhaps it was less mechanically efficient as well. Frederick (1985) estimated that every 100 g of weight added to each foot during running raises the aerobic demands of running by about 1%.

In addition, Chang et al. (2000) reported that the increase in the total energetic cost of running might also result from an increase in the muscle forces to sustain the increase of the limb inertia.

Although, previous study reported that additional masses may be increasing the internal work of the segment and metabolic demands, the overall strategies for progressing along the ground have not been changed. From this information, in the DST one may argue that skis may not importantly affect the leg kinematic and mechanics, but their masses may have an effect on the energy cost of the locomotion.

2.4.2.2 Pole effects on locomotion patterns.

In the DST poles constituted two additional supports that can be used as generator of additional forces and / or in the stabilisation of the gait, by increasing the base of support (Jacobson et al., 1997).

Since poles are commonly used in trekking (i.e. Nordic walking), numerous researchers investigated their effect on the walking gait mechanics. Willson et al. (2001) observed a more flexed knee during the stance phase that reduced the vertical bone forces. Therefore, walking with poles was reported as a less harmful mode of exercise since poles reduced the stress on the lower extremities by transferring part of the load to arms and shoulders joints (Jacobson et al., 1997; Willson et al., 2001; Schwameder et al., 1999). This has been confirmed in downhill terrain where the poles reduced the knee reaction force of 15-20% and would constitute an efficient way of preserving the patellofemoral and knee tendon (Schwameder et al., 1999). Similarly, as a means of joint protection, a pole would help in the absorption and generation of energy in the gait in the case of physical tiredness or expertise (Willson et al., 2001). These observations have been recently contradicted by a study from Jollenbeck et al., (2006), showing no reduction of the vertical reaction force during Nordic walking.

Authors reported that Nordic walking constituted a different way of generating propulsive forces since the authors reported an increase of walking speed with poles (Willson et al., 2001; Jollenbeck et al., 2006). In specific conditions, such steep downhill terrain, Nordic walkers have been reported to change their posture, using the poles as an aid to slow the body.

Poles may be affecting the locomotory patterns in walking. In DST, one may expect that the cumbersome of the poles and the utilisation of poles for propulsion may be triggering a specific segmental organisation.

2.4.3 Summary

Humans, when subjected to a challenging environment, adopted locomotor strategies to counteract balance impairment. On slippery floor, previous research (Marigold et al., 2003) reported that, with practice, specific recovery strategy was employed.

Poles and additional weight to the extremities may be responsible to changes in the kinematics of the locomotor patterns. In the DST, it is supposed that the environmental conditions and materials used will be affecting the segmental organisation in order for the skier to 1) keep his balance and 2) accelerate his body centre of mass forward.

2.5 Summary of the literature review

The DST is a technique of cross-country skiing that has been reported to have been used for thousand years. In this technique the limbs are travelling in the sagittal plan with qualitative observation recalling movement such as walking and running. However, the characteristics of the DST showed strong specificities versus walking and running with the use of skis and poles and the involvement of a gliding phase in the movement. Those particularities make the DST an original locomotion, often reported as an adaptation of walking and running to a snowy environment.

Researchers have been using numerous tools (i.e. force transducer, digital video cameras, optical cameras or pan-tilt cameras) to record human movement. The quality of the measured data from each apparatus is dependant on the task and environmental conditions. Appropriate measurement technique should be chosen to take into account the characteristics of the DST.

Numerous analytical techniques have been reported for understanding human movement strategies. Qualitative and joint angular analyses have been hugely important in the description of segmental function in walking and running. Coordination analyses provided a further understanding of the relationship existing between the segments for the accomplishment of specific task. Mechanical analyses provided a strong background on the overall mechanisms for moving along the ground in walking and running.

The DST literature showed a lack of data in most analytical techniques reported, limiting the general understanding of the mechanisms used for progressing on the snow.

Specific segmental strategies used in walking and running to cope with gliding environment and additional material may showed similarities with the DST locomotion.

2.6 Research question

With regard to the current DST literature, the case has been made that a lack of data limits our understanding of the technique used by skiers. DST represents a locomotor adaptation of humans for their transportation in a specific and challenging environment.

A large body of research took different theoretical approaches to consider how locomotions are performed. The similitude of DST with walking and running supposed that the techniques and analytical methods used for the investigation of human locomotion might be applied to DST.

Further knowledge on the biomechanics of the DST may develop our understanding of the adaptational strategies used by humans for locomotion. Additional benefits of the research may be directed towards coaches in their quest to improve performance in DST.

The research question of this work can be stated as follows: What are the biomechanical strategies developed by expert cross-country skiers to progress along the ground in DST? To answer this question various analytical techniques have been used underlying the following objectives:

1. Describe the movement strategies that generate locomotor displacement in the DST.
2. Determine the overall mechanics of the DST to progress along the ground.
3. Understand the role of the joints in the generation of horizontal body centre of mass velocity.
4. Understand the roles of poles in the DST locomotion.

5. Develop an understanding of the techniques used for increasing speed in the DST

These objectives will be addressed in four main studies:

Study 1: a description of the joint angular patterns in the DST,

Study 2: a mechanical description (mechanical energies and mechanical work of the body centre of mass) of the DST locomotion,

Study 3: a kinematic and mechanic comparison (cycle, body joints angulations, inter-limb and intra-limb coordination, mechanical work) of the DST with the DST without poles,

Study 4: a kinematic comparison (cycle, body joints angulations kinematics) of the DST under two different speed conditions.

CHAPTER 3. MATERIALS AND METHODS

3.1 Recording system most suitable for DST

The literature review (section 2.2) highlighted the different kinematic and kinetic systems used for the analysis of human movement. Kinetic studies required expensive equipment that is hardly suitable for protocols requiring testing in the outdoor, snowy environment. The lack of kinematic data in the DST literature justified the need for a thorough kinematic study of this locomotion. In DST, the constraints of the environment (skis, poles and snow) also limited the choice of the method for data collection to digital cameras. The limitations of the automated and semi-automated video systems (i.e. Vicon or Qualysis motion systems), indicated that these optical system would not be applicable to the DST as the brightness of the snow may deceive the marker tracking system. In addition, the stride length reported in DST (Gagnon, 1981; Nilsson et al., 2004) reaching up to 5 meters may involve a too large volume to allow an accurate and precise recording with automated motion analysis systems. Pan-tilt camera system have been reported as a solution for sporting activities (i.e. ski jumping, ice skating) requiring large recording field. The reported cycle length of 5 meters long in DST (Bilodeau et al., 1996; Nilsson et al., 2004) supposed that pan-tilt cameras were not a pre-requisite for reliable data collection. The sampling frequency of digital cameras is sufficient for the recording of movement such as the DST. The processing of the time-varying data needs to respect the sampling theorem (Winter, 1990). The sampling theorem essentially states that the sampling frequency must be twice as large as the greatest frequency presented in the actual signal though preferable much larger. Previous studies reported a cycle frequency in DST of 1.2 Hz for a maximal skiing speed (Nilsson et al., 2004). As each cycle involved a flexion / extension phases of the joints, the segments frequency may be doubled. Digital camera allows a sampling frequency of 50 Hz which is much more than twice as large as the highest frequency involved in DST. Therefore, it appeared that the choice of conventional digital video cameras would be relevant for the study of DST.

The DST is a sporting activity that is practised on snow. Roller-skis have been proposed as an alternative for reproducing the movement in a laboratory environment (Millet et al., 1998a, b; Holmberg et al., 2005). However, some important issues can be reported with roller skis during the leg propulsion mechanism. The method of propulsion on roller-skis is quite different from that of the DST on snow since the grip generated during propulsion is dissimilarity dissimilarly achieved; in roller-skiing, the propulsion is achieved from the blockage of the rear wheel, missing out the difficult requirement of the interaction between the snow and the ski wax. In addition, previous studies have shown that kinematic differences exist between DST on skis compared to roller skis (Pinchak et al., 1987). They also reported that larger skiing velocities were achieved with roller skis compared to snow skis. Therefore, testing DST in its natural environment seems to be more appropriate for the description of the locomotion.

3.2 Preliminary study

Preliminary studies were undertaken in order to determine if common characteristics exist in DST kinematics patterns and ascertain their consistence between and within subjects. In addition, these preliminary studies tested the appropriateness of the materials and methods selected for the study of DST.

3.2.1 Pilot study: reproducibility of angular patterns in DST

3.2.1.1 Introduction - reproducibility of angular patterns in DST

In walking and running, repeatable kinematic patterns within and between subjects have been reported (Winter, 1984). Therefore many researchers limit their analysis of walking or running to a small number of repeated cycles (1 to 3) (Murray, 1967; Mann and Hagy, 1980; Nilsson et al., 1985; Milliron and Cavanagh, 1990; Kivi et al., 2002). In the DST literature, kinematic analysis has essentially been undertaken for a single cycle (Gagnon, 1980; Norman and Komi, 1987; Komi et al., 1982). Therefore, it is still unknown if the kinematic patterns are intra-individual and inter-individual reproducible in DST. This information would be of great importance for reducing the amount of data to be collected to represent the DST angular patterns in this and other studies.

Methods for assessing the reproducibility of measurements within sports science have been scrutinised over the last 10-15 years (Atkinson and Nevill, 1998; Hopkins, 2000). Researchers quantified reproducibility using different statistical methods (Hopkins, 2000). The analysis of the means and variability (i.e. standard deviation, typical errors, coefficient of variation) are important types of reproducibility measures. The use of retest correlation (i.e Pearson correlation, Intraclass correlation) constitutes another good measure of the reproducibility of measurement (Hopkins, 2000).

The pilot study aims to test the reproducibility of kinematic measurements for a group of cross-country skiing competitors. This may provide an overview of the reproducibility of the kinematic patterns in DST but also a test of the appropriateness of the method used.

3.2.1.2 Methods - reproducibility of angular patterns in DST

3.2.1.2.1 Subjects

Six male cross-country skiers participated in this study (Mean ± SD age 20 years ± 2.6, height 1.78 m ± 0.05, mass 69.8 kg ± 6.9). Their expertise ranged from regional to national level.

3.2.1.2.2 Experimental procedures

The test was undertaken on an outside cross-country skiing snow track. The entire test was carried out during a short period of the day in order to minimise the change in the snow properties. Each subject performed 15 km distance at a sustained velocity (i.e. "fast velocity"), executing 6 laps of 2.5 km each using the diagonal stride technique (DST).

They were instructed to maintain a fast skiing speed over the whole duration of the 15 km course. The lap time was recorded each time subjects crossed the starting line. At the end of each lap, a 70 meters long flat terrain, slightly uphill, was set up for data collection. This allowed the subjects to maintain a stabilizing skiing speed during the data collection period and the terrain chosen in reference to previous work (Marino et al., 1980) which showed that a slightly uphill terrain was able to discriminate subjects of different performance abilities.

The snow consisted of large, wet snow grain making the snow surface relative soft with a snow temperature of +6°C. The weather was sunny, relatively warm (+14°C) with no wind. When asked, all subjects agreed that the skiing conditions were 'averagely gliding'. The subjects used their own equipment and waxed their classical skis to get an optimum grip and glide.

3.2.1.2.3 Data collection

Data were collected for 5 laps for each subject. Data from the first lap was dismissed as the skiers entered the recording area with an accelerating speed. The participants were filmed in the sagittal plane using a digital camera (Panasonic NV-GX7 EG, PAL., 25 frames / s) fixed on a tripod positioned 10 meters perpendicularly from the ski tracks (figure 3.1). The optical axis of the camera was vertically centred on the 1 meter high point. The shutter speed of the camera was set at 1/250 s giving regard to the velocity of the movement and the available lighting conditions. The video recording area was situated at the end of the 70 m ski path. The camera field was 8 meters wide in order to record a full skiing gait cycle according to cycle length values previously reported in the literature (Dillman et al., 1979; Gagnon, 1980, 1981; Bilodeau et al., 1992, Nilsson et al. 2004). At the end of the test, a reference 3 meter length was filmed in the central filmed portion of the track to be use for calibration during the digitising process.

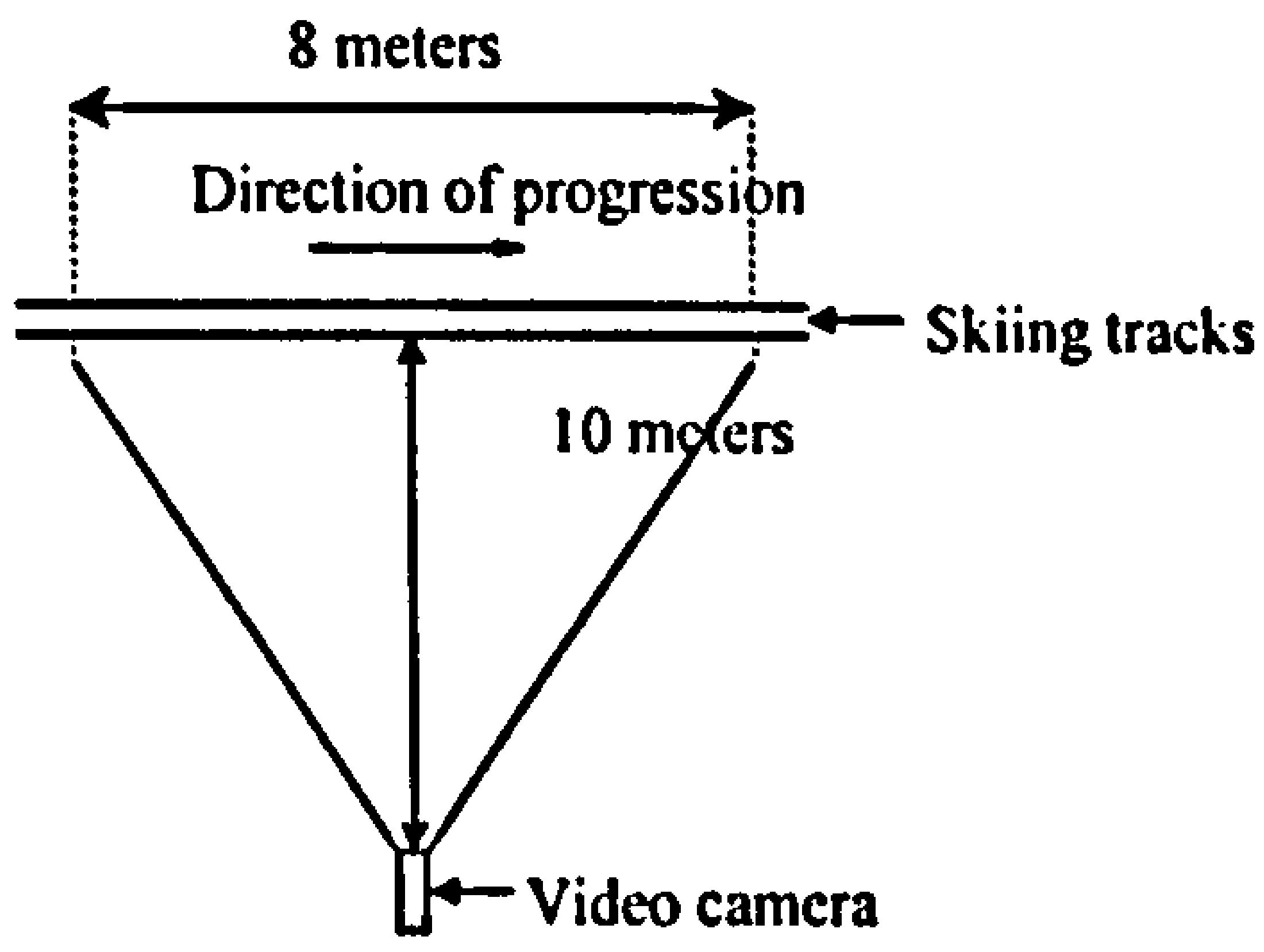


Figure 3.1: Experimental set up

3.2.1.2.4 Data treatment

Video images were digitised frame by frame and point by point between two consecutive plants of the right ski pole. For each frame the hip, the knee and the ankle joints were manually digitized using a locally written program (University of Leeds, 1996). All kinematic coordinates were smoothed using a Butterworth Low-Pass filter with padded end-points. It has been reported that filtering data could induce some errors on both side end points (Vint and Hinrichs, 1996). To avoid those, image sequence padding is often used for example by adding 10 images before the beginning and 10 images after the end of the actual sequence of images of interest.

With a Butterworth filter, a preliminary study has to be done to select the optimal cut-off frequency. This selection was made over the angular parameters (i.e. thigh and knee angular displacement) analysed in this pilot study and detailed further in the text. The determination of the cut-off frequency was realised with data from one subject.

- Selection of an appropriate cut-off frequency

Using a Butterworth filter, the specification of a parameter that effectively fixes the amount of noise to be removed is very important for efficient noise removal. The procedure for determining the suitable cut-off frequency can be realised with a residual analysis. The residual analysis (R(fc)) of the difference between filtered and unfiltered signals was done over a wide range of cut-off frequencies using the following formula:

Equation 3.1: $R(fc) = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(X_i - X'_i)^2}$ **(Winter, 1990),**

where X_i = raw data at *i*th sample and X'_i= filtered data at the *i*th sample

The cut-off frequency was graphically determined by the experimenter. A typical curve of the residual analysis shows that at certain cut-off frequencies (5 Hz on figure 3.2), the pattern reached a straight line. This area is called the transition region because it involves a transition in the pattern from a curved to a straight line. The prolongation of this linear curve on the y-axis and then on x-axis, as shown on the figure 3.2, results in the determination of the ideal cut-off frequency for the data treated.

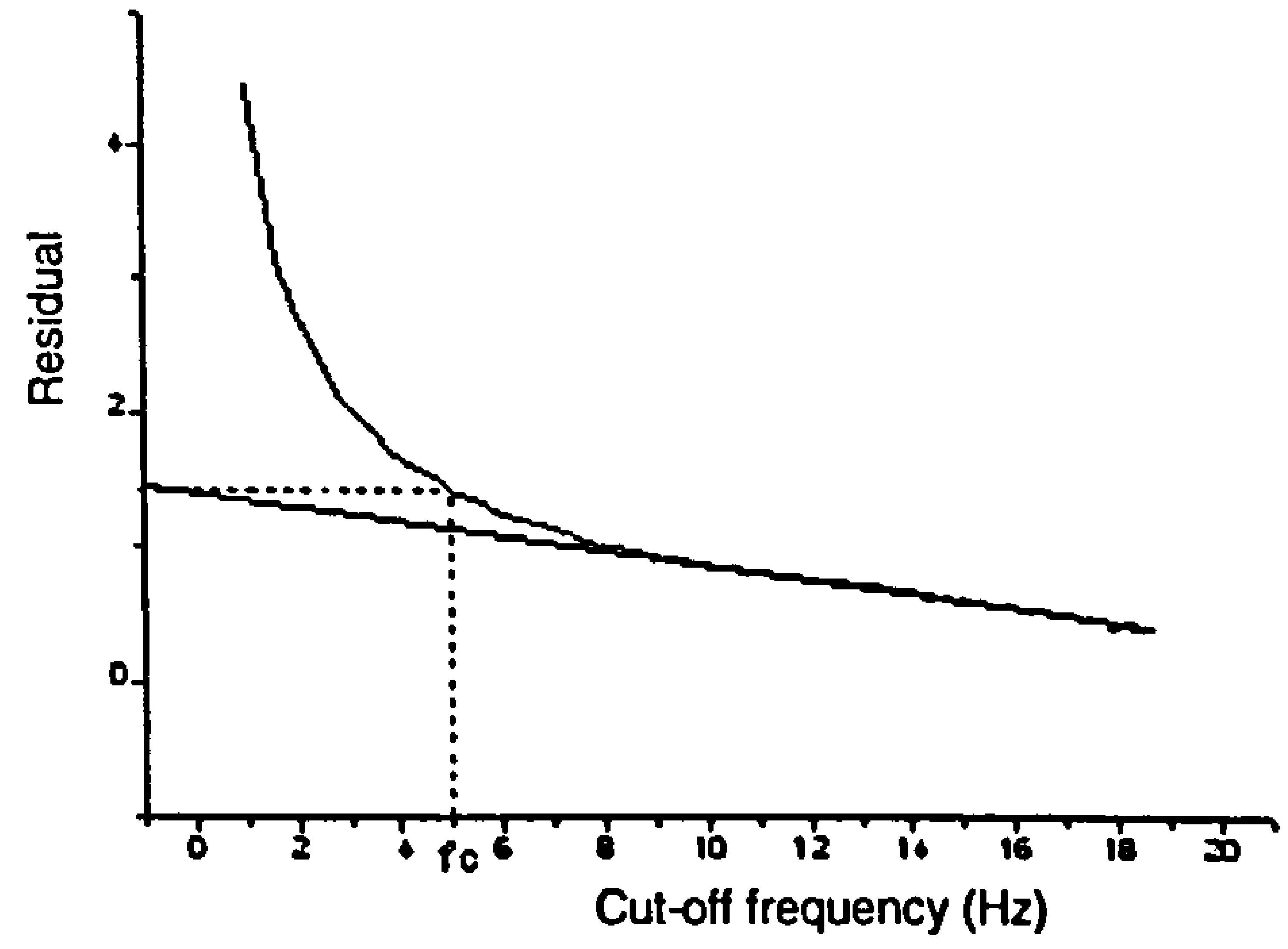


Figure 3.2: Plot of the residual between filtered and unfiltered signal as a function of the filter cut-off frequency (adapted from Winter, 1990)

The residual was calculated for cut-off frequencies ranging between 2 to 18 Hz with an increment of 0.5 Hz. For both thigh and knee angular displacement data, a cut-off frequency of 4.5 Hz was determined to be suitable. This result was in agreement with previous biomechanical study on DST (Komi and Norman, 1987).

3.2.1.2.5 Data analysis

Five cycles were analysed. Cycle velocity (CV) was calculated as the distance travelled during one cycle (CL) divided by the duration of the same cycle (CD):

$$CV = CL \div CD$$

The thigh segment angle and knee angle were calculated from the smoothed coordinates of the hip, knee and ankle using the formula:

Equation 3.2: $\theta_{ij} = \arctan(y_j - y_i)/(x_j - x_i)$ *Winter (1990)*

The thigh and knee joints were determined as shown in the figure 3.3.

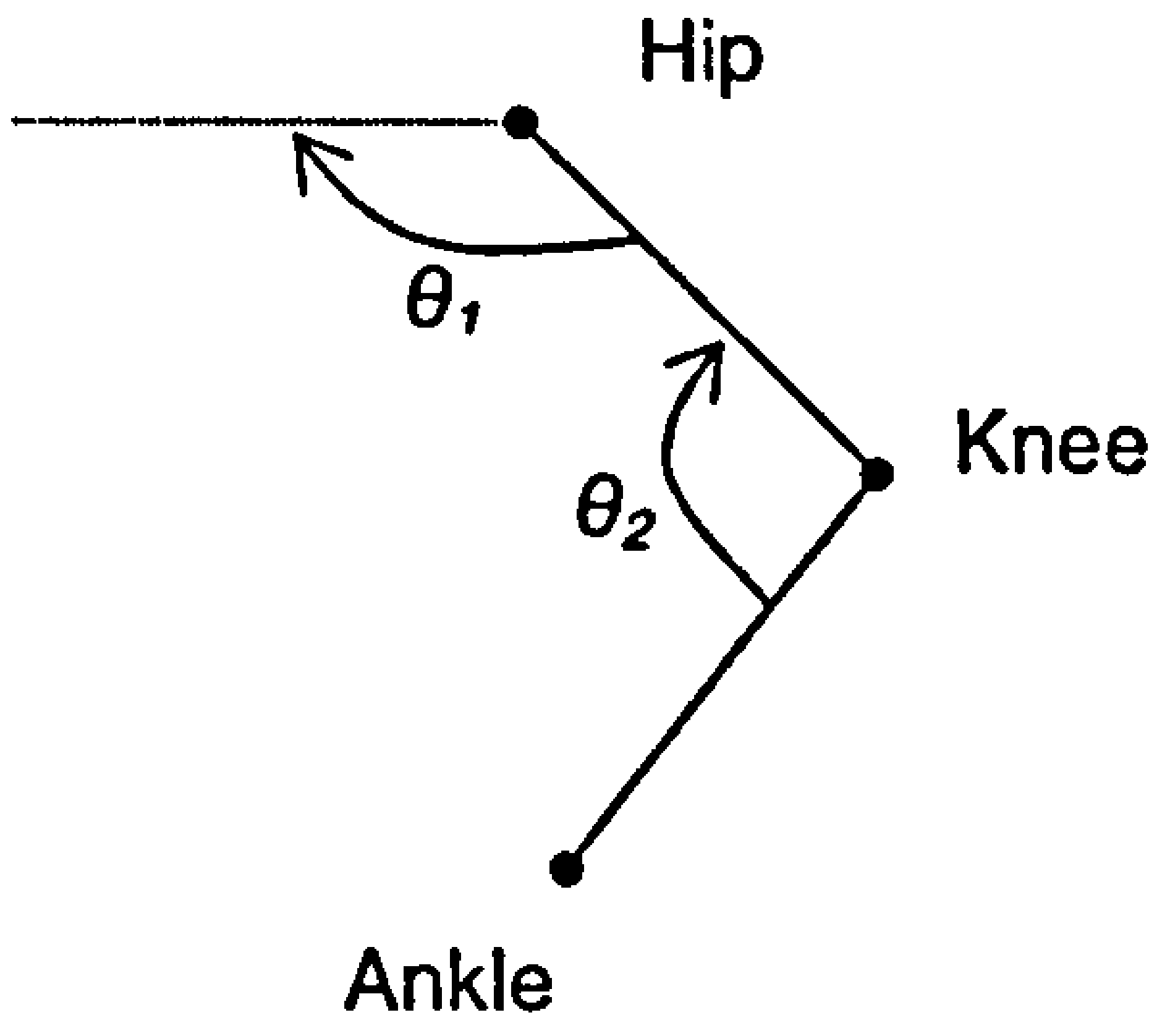


Figure 3.3: Thigh segment angle (01) was defined as the angle between the straight line hip-knee and the left horizontal. The knee angle (02) is the angle between the thigh and the shank.

For each cycle analysed, the angular displacement time course of the thigh and knee were analysed.

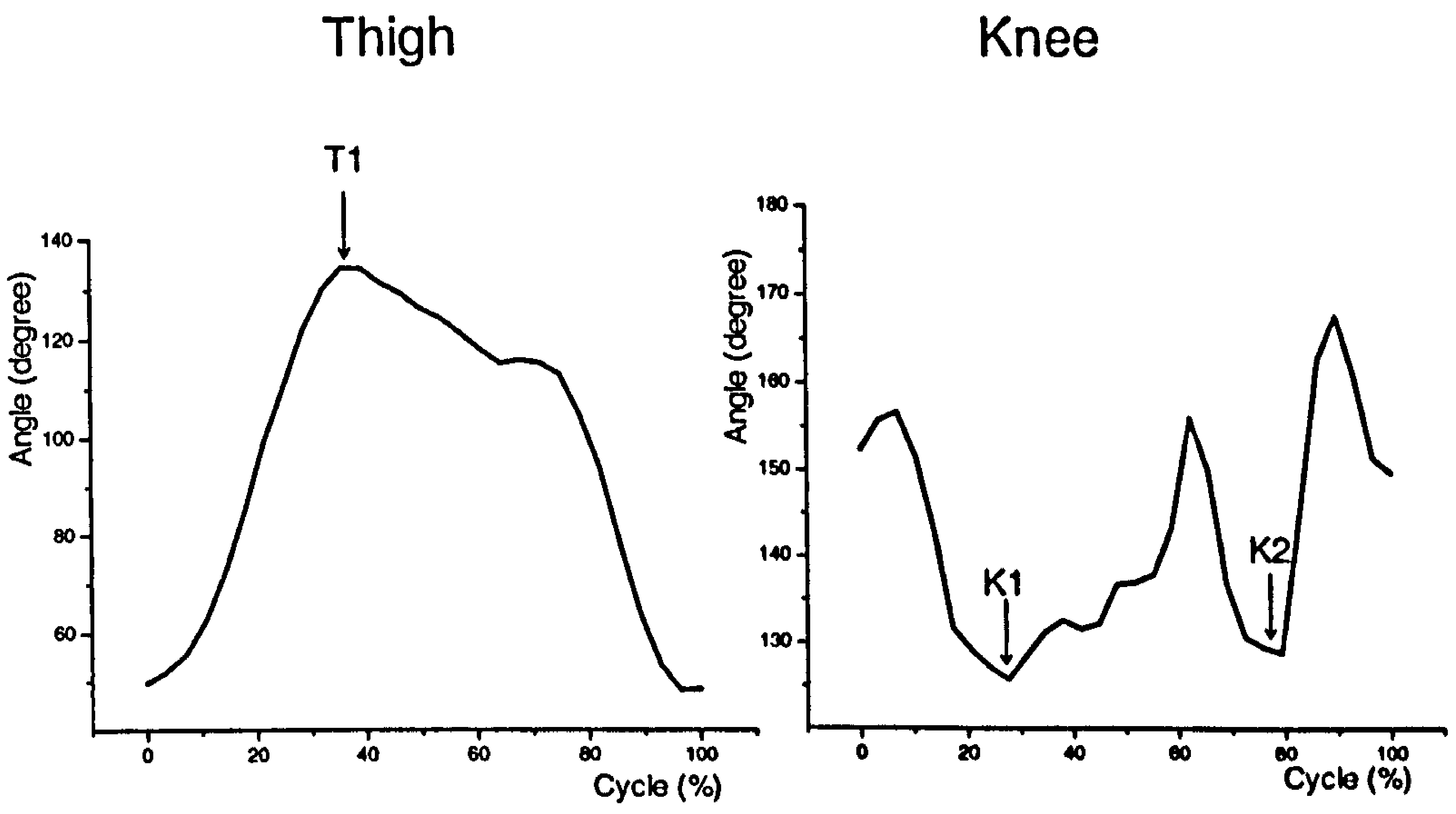


Figure 3.4: Thigh segment and knee angular patterns for an entire DST cycle. T1, K1 and K2 represent the maximum flexion of the thigh segment, the first knee flexion and the second knee flexion peaks respectively.

To assess the reproducibility of the kinematic patterns over the 15 km test, the following parameters were used for analysis:

- the temporal and spatial values of the maximum flexion of the thigh (figure 3.4; T1),
- and the temporal and spatial values of the knee angular flexion peaks (figure 3.4; K1, K2).

Temporal values (expressed as a percentage of the cycle) and spatial values (expressed in degrees) were extracted from the time course curves of the thigh and the knee (figure 3.4).

3.2.1.2.6 Statistical Analysis

The temporal and spatial values of T1, K1, and K2 were averaged (± StD) over each lap. To investigate the inter-individual variability, the coefficient of variation was calculated for each parameter as the ratio between the standard deviation (StD) and the mean of the data. The reproducibility of the kinematic patterns over the test was assessed using an Intraclass Correlation (ICC) coefficient. ICC has been reported as a more appropriate indicator of test-retest reliability compared to the Pearson's correlation coefficient (Vincent 1999). An ICC of 0.7- 0.8 was considered to be an acceptable correlation, 0.8-

0.9 to be a good correlation and > 0.9 to be a high correlation (Vincent 1999). The ICC coefficient was performed using SPSS 14.0 Software for Windows (SPSS Inc., Chicago, Ill., USA) with a significant level of as $P < 0.05$.

Additionally, the within-subject standard deviation referred as Typical Error Measurement (Hopkins, 2000), expressed as a percentage, was calculated. It represents a quantification of the standard deviation in each subject's measurements between tests. In other words, the Typical Error is a measure of the DST kinematics patterns consistency within subjects.

3.2.1.3 Results - reproducibility of angular patterns in DST

The group of skiers executed the tasks with cycle velocities ranging from between 3.9 m·s^{-1} and 3.1 m·s^{-1} representing a difference of 20 % between the fastest and the slowest cycle velocity tested. Large variations between subjects were also observed in cycle length and cycle frequency with values evolving from 3.5 to 4.9 m and from 0.8 to 1 Hz respectively.

The mean temporal and spatial parameters calculated were rather consistent between the laps (table 3.1). Depending on the parameter, the coefficient of variation ranged from 2.0 % to 7 %, providing an estimation of the variability existing between subjects. It was observed that the difference between subjects was larger for the spatial parameters than for the temporal parameters (table 3.1).

Table 3.1: Average temporal and spatial values ± S.D. for T1, K1 and K2. In brackets is the coefficient of variation.

	Mean ± S.D.	Mean ± S.D.	Mean ± S.D.	Mean ± S.D.	Mean ± S.D.
Temporal parameters	Cycle 1	Cycle 2	Cycle 3	Cycle 4	Cycle 5
T 1 (% of cycle)	38.7 ± 1.2 (3.1%)	36.7 ± 1.0 (2.8%)	37.3 ± 1.4 (3.7%)	37.3 ± 1.6 (4.2%)	38.8 ± 1.5 (3.8%)
K 1(% of cycle)	28.0 ± 1.2 (4.2%)	28.2 ± 1.3 (4.6%)	28.5 ± 0.9 (3.3 %)	28.3 ± 1.0 (3.2%)	28.4 ± 1.0 (3.5%)
K 2(% of cycle)	80.7 ± 2.3 (2.9%)	81.5 ± 2.1 (2.5%)	82.2 ± 2.1 (2.6%)	81.0 ± 2.8 (3.4%)	81.0 ± 1.6 (2.0%)
Spatial parameters					
T 1 (degrees)	127.9 ± 6.2 (4.8%)	126.0 ± 5.1 (4.1%)	125.8 ± 4.7 (3.7%)	125.4 ± 7.3 (5.8%)	127.2 ± 7.2 (5.6%)
K 1(degrees)	121.8 ± 7.2 (5.9%)	118.2 ± 6.7 (5.7%)	119.9 ± 8.3 (6.9%)	118.8 ± 8.5 (7%)	118.3 ± 5.8 (4.9%)
K 2 (degrees)	129.4 ± 4.3 (3.3%)	129.4 ± 2.6 (2.0%)	130.0 ± 7.0 (5.4%)	129.2 ± 8.5 (6.6%)	128.2 ± 4.1 (3.2 %)

All parameters showed acceptable to good ICC coefficients, except for the temporal value of the second knee peak flexion (table 3.2).

Table 3.2: Intraclass correlations coefficients for each parameter studied. * P<0.05; ** P<0.01; *** P< 0.001.

Temporal parameters	Intraclass Correlation
Thigh 1	0.792**
Knee 1	0.978***
Knee 2	-1.185
Spatial parameters	
Thigh 1	0.983***
Knee 1	0.967***
Knee 2	0.693*

Average typical error was reported to range between ±1.0 and ±1.3 % of the cycle for temporal parameters and between ±2.0 and ±2.5 degrees for spatial parameters (table 3.3). This result suggested that skiers showed a small intra-subject variability.

Table 3.3: Maximum, minimum and mean Typical Error (expressed as a percentage of the cycle or in degrees) calculated over the 5 cycles.

	Typical error (% of the cycle)			Typical error (°)		
	T 1- Temporal	K 1- Temporal	K 2- Temporal	T1- Spatial	K1- Spatial	K2- Spatial
Max Typical Error	± 1.9	± 1.9	± 1.2	± 2.9	± 2.7	± 5.1
Min Typical Error	± 0.9	± 0.5	± 0.8	± 1.9	± 1.6	± 1.9
Mean	± 1.2	± 1.3	± 1.0	± 2.2	± 2.0	± 2.5

3.2.1.4 Discussion / Conclusion - reproducibility of angular patterns in DST

The purpose of the pilot study was to investigate the spatial and temporal reproducibility of kinematic patterns in DST. To accomplish this purpose, five cycles per skier were analysed across a 15 km skiing test.

The values of cycle velocity, cycle length and cycle frequency and knee angulation were consistent with previous work investigating the DST in long distance racing conditions (Dillman et al., 1979; Komi et al., 1982). Differences in the skiing velocity, cycle length and cycle frequency have been observed between the skiers of various level of performance.

The coefficient of variation provided an estimation of the inter-individual variability in the kinematics of the DST. Overall, the coefficients of variation reported were relatively low (i.e. reaching a maximum of 7 %). This suggested that strong inter-individual patterns existed in DST. Larger coefficients of variation have been observed for spatial parameters (5-7%) indicating larger inter-individual differences in spatial parameters. This is in accordance with previous work on walking and running, showing kinematic variability between participants (Winter, 1983; Diedrich and Warren, 1995). This may be explained by the difference in the stature and morphological characteristics of the skiers tested, and by differences in the skiing technique and style. In addition, the skiing speeds were different between the skiers, ranging from 3.1 to 3.9 m/s.

The high ICC coefficients showed high level of reproducibility for most of the kinematic patterns tested during the whole duration of the skiing test. However, the temporal and spatial parameters related to the second peak of knee flexion showed lower ICC coefficients. As the second peak of knee flexion (K2) acted to propel the body, this result suggested that more kinematic variability may be occurring during the propulsion phase. In accordance with previous studies (Hoffman and Clifford, 1992; Smith, 2003) this observation suggested that the propulsion phase is a challenging skill for the skier to perform.

The calculation of the Typical Error represented a statistical means for quantifying the variability existing within sets of data from the same skier. It was shown that overall the skiers changed their kinematic temporal parameters within a range of ±1.3 % of the cycle. Across the five cycles, joint angular measurements appeared to be evolving within a range of ± 2.5 degrees. This calculation of error between the reported data developed from variability within the subjects but also developed from error due to the experimental method (i.e calibration error, perspective error, digitising error).

This preliminary study brought an initial insight on the biomechanics of the DST that had some implications on the selection of the experimental method that followed. First, it provided a range of cycle parameter values (i.e. cycle velocity, cycle length and cycle frequency) that can be expected from experienced skiers during a racing event. The cycle length evolved from 3.5 to 4.9 meters making the recording field chosen (8 m) sufficient for the recording of an entire cycle.

Second, a strong reproducibility in the DST angular patterns (both temporally and spatially) during the test suggested that 1) the skiers developed reproducible DST movement patterns and 2) that the experimental method used in the preliminary study was sufficient to measure the kinematics of the DST.

Therefore, it appeared relevant for the next experimental method to select the same experimental set-up. In addition, since the kinematic patterns may be reproducible, the number of cycles to be analysed, may be reduced to limit the amount of digitizing work.

3.3 Experimental protocol and methods

This section 3.3 will present the subjects, experimental set-up, protocol and data treatment of the main experiment that were similar for all four studies (see chapter 4).

The data analysis will also be presented and summarised. This choice was motivated by the fact that similar kinematic parameters were investigated for several studies, involving different skiing conditions. The mechanical data analysis was also presented in this section to show the methodological continuity between kinematic raw data and mechanical analyses.

Therefore, the choice was made to report in one chapter the materials and methods used in a number of studies. Some reference will be made to this chapter in the appropriate parts of the results section.

3.3.1 Subjects

Eight male competitor cross-country skiers volunteered to participate in this study. The subjects were sport students, all competing at a national level. Their characteristics are showed in the table 3.4. The subjects were cross-country skiing at least four times a week during the skiing season (i.e. October to April). All subjects had stabilised DST, since they had between 6 to 12 years of regular cross-country skiing practise. All skiers indicated that they had followed a large amount of training in DST and experienced training sessions of DST without poles.

Table 3.4: Characteristics of the subjects in the study.

Parameters	Values
Age (years)	19.2 ± 0.7 (3.6%)
Height (m)	1.81 ± 0.05 (2.7%)
Mass (kg)	70.9 ± 5.7 (8.0%)
VO_2 max reported (ml·kg·-1·mn-1)	76.8 ± 4.9 (6.4 %)
Ski length (m)	2.04 ± 0.04 (2.0%)
Pole length (m)	1.52 ± 0.04 (2.6%)

The subjects were homogeneous in all parameters reported.

3.3.2 Equipment and set up

The test was undertaken on an outside cross-country skiing snow packed track, especially prepared for the experimentation. In reference to previous studies the test was undertaken on a 200 meters flat terrain slightly uphill (2%). This type of terrain has previously been shown to be able to discriminate different level of performance (Marino et al., 1980; Komi et al., 1982). On the day of the test, the weather was sunny; with a slight head wind and an average temperature of 5° Celsius. The snow was constituted of large transformed grains with a temperature of 2-3° Celsius, and was described as gliding by all subjects. In accordance with the air and snow condition, a Red Kick Klister (Swix®, 0 - 5° C) grip wax was used by all subjects. In order to avoid any possible modifications in their normal movement patterns all skiers used their own skis and poles. All subjects used racing DST skis and poles of the same quality, so that minimum inertial differences can be expected between subjects.

The entire test was carried out during a 4 hours period of the day in order to minimise the change in the snow properties.

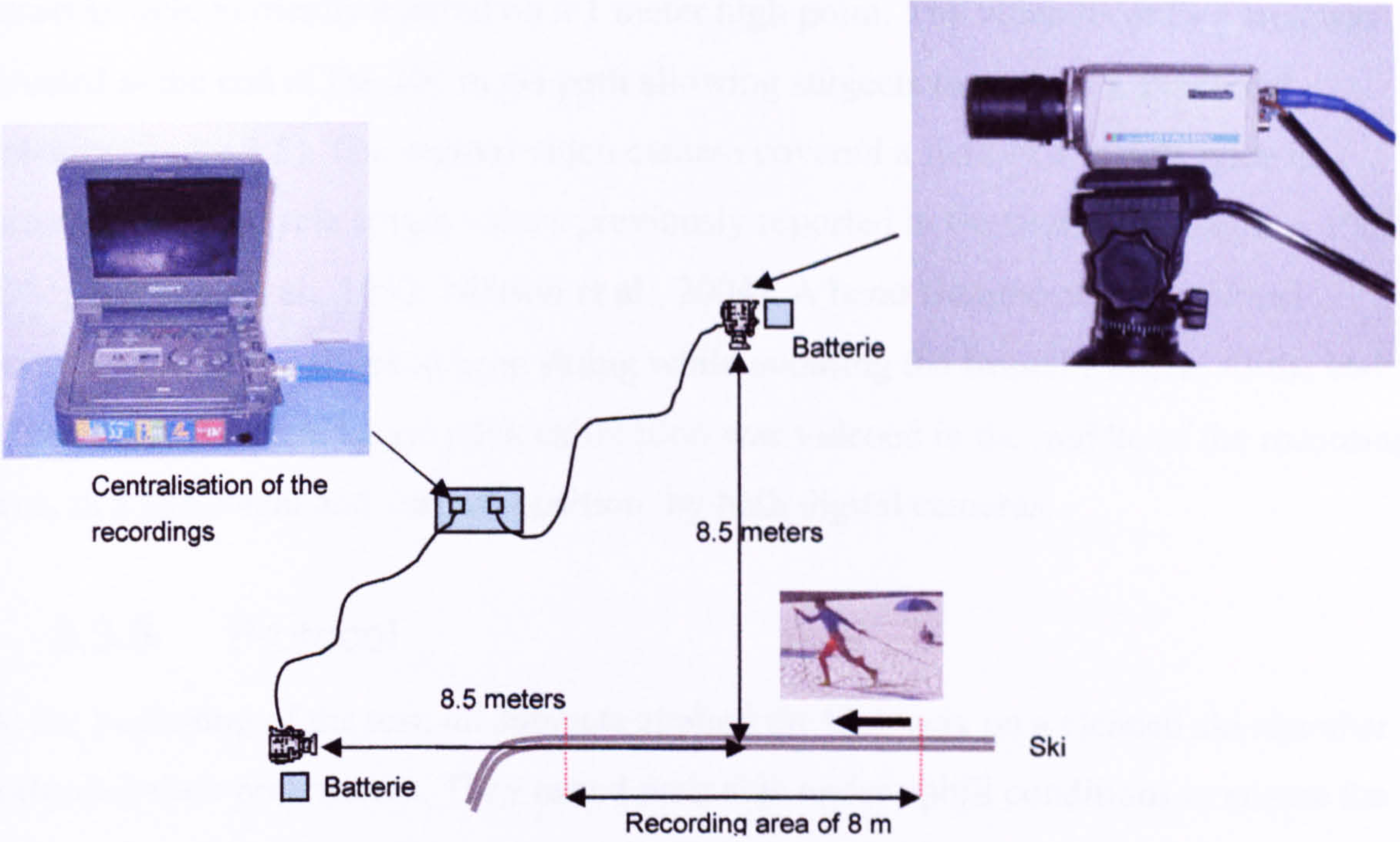


Figure 3.5: Experimental set-up.

The kinematic data were collected using two digital video cameras (Panasonic WV-CP454E), recording at a sampling rate of 50 fields per second and two digital video walkmans (Sony GV-D900 E). The shutter speed of the camera was set at 1/500 s giving regard to the velocity of the movement and the available lighting conditions. In accordance with the theorem of Shannon, the sample rate of 50 Hz, was more than 3 times larger than the cycle frequency previously reported (Gagnon, 1980, 1981; Nilsson et al., 2004). The distortion of the lens was reported to be less that 3 % by the manufacturer. Both cameras were controlled by the same experimenter through the digital video walkmans. The equipment (cameras and video walkmans) were protected from the low position of the sun in the sky using parasols. The cameras were powered by two 12 volts batteries, allowing sufficient power for running an afternoon in cold environment. The cameras were set up in order to obtain frontal and sagittal views of the skiers. Sagittal views were recorded from a camera disposed perpendicularly to the ski tracks. Frontal views were obtained by placing the optical axis of the camera in line with the ski tracks in the film portion of the ski circuit (figure 3.5). Both cameras were positioned at 8.5 m from the middle of the recording area. In addition, the optical axes of the cameras were level and placed at an angle of 90° to each other using a theodolite and in accordance with the software Ka Video (Schleihauf, 2000). The optical axes of the cameras were vertically centred on a 1 meter high point. The video recording area was situated at the end of the 200 m ski path allowing subjects to achieve a stabilized velocity (figure 3.5). The sagittal video camera covered a field of 8 meters wide in accordance with cycle length values previously reported in the literature (Gagnon, 1980, 1981; Bilodeau et al., 1992; Nilsson et al., 2004). A bend situated after the filmed portion allowed the skiers to keep skiing while avoiding the frontal camera. At the end of the test, a 2 meters length stick calibration was videoed in the middle of the recording area, in a horizontal and vertical position, by both digital cameras.

3.3.3 Protocol

At the beginning of the test, all subjects applied the kick wax on a cleaned ski chamber following their preferences. They tested their skis under uphill conditions to ensure the kick wax employed was appropriate and efficient. All subjects considered themselves to have a good grip. A warm-up consisted of skiing at a slow pace for 20 minutes.

Skiers had 5 mock passages to be familiarised with the ski tracks and organised themselves to start the right ski propulsion at the beginning of the recording area.

The actual test was conducted under three different conditions:

1. The subjects were first asked to ski 3 times, at a "normal" speed (DST_n) as they would choose for sustaining a training session of 2 hours (condition 1).
2. Second, the subjects were asked to ski 3 times without poles at a normal speed (DSTwp), representing a training pace (condition 2).
3. For the last condition, the skiers were asked to ski 3 times at a "fast" speed (DST_f) as they would be able to sustain over a 10 km racing (condition 3).

The recording of three trials per condition assured the acquisition of at least one DST cycle for analysis for each subject. Between each passage, the subjects had at least 5 minutes recovery to minimise the effects of fatigue.

3.3.4 Data treatment

3.3.4.1 Digitising process

From each skiing condition, the video recordings from the sagittal camera were converted into a sequence of images to be digitised using the program KA-Video (Schleihauf, 2000) and validated by Monteil et al. (1996). For each image, the wrist, elbow, shoulder, hip, knee, ankle, heel, toe, from both side were manually digitized, generating a 12 segments model of the skier (Figure 3.6). For each condition and subject, the digitising was made in order to obtain an entire DST cycle plus an additional 10 images before and after the actual sequence. The cycle was defined as the period between two consecutive lifts from the snow of the right ski (figure 3.9). The pre and post added digitised data were needed for avoiding the end point error during the filtering process (Vint and Hinrichs, 1996). Each digitised sequence was checked once and re-digitised if any error in the location of the joint was spotted.

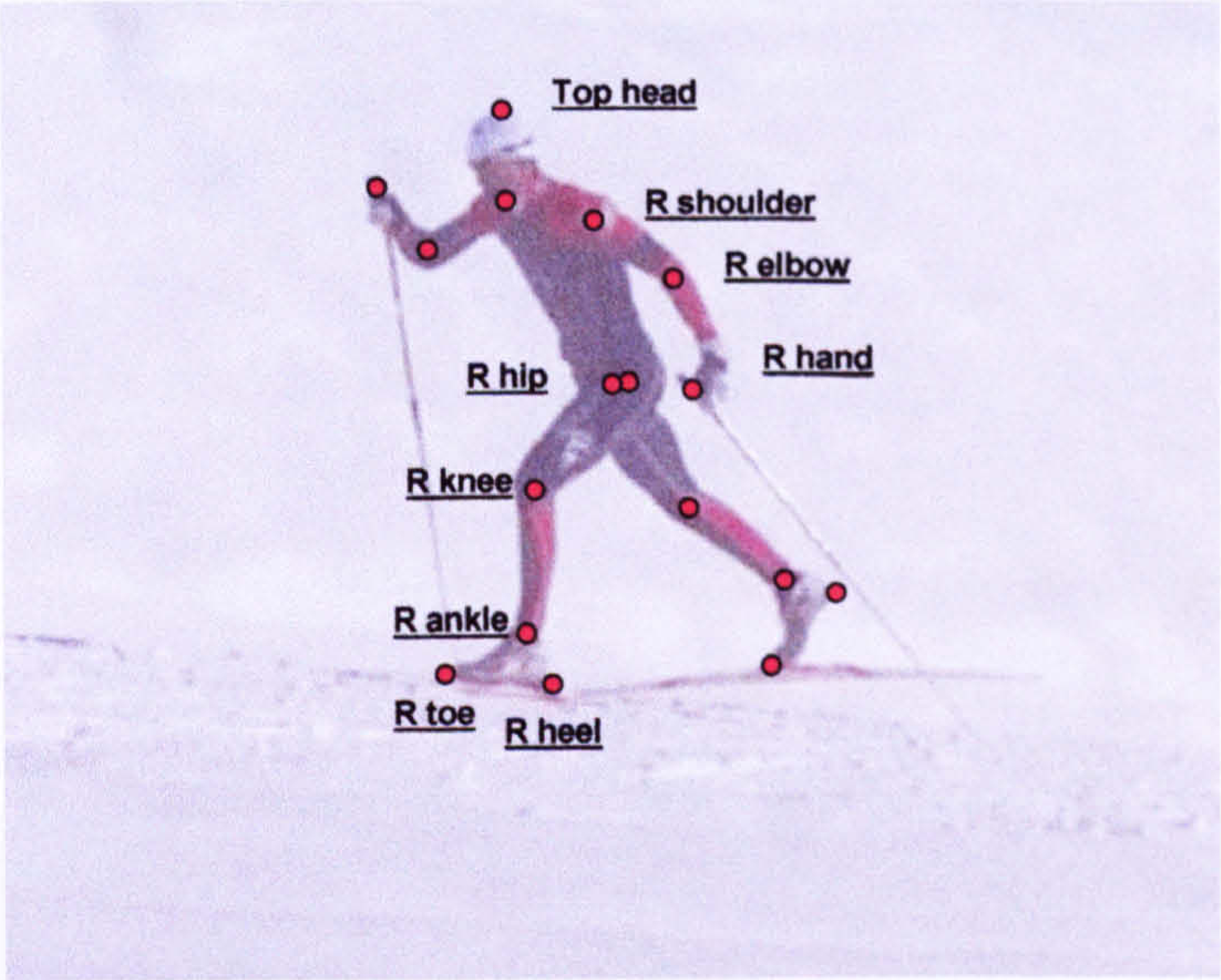


Figure 3.6: Points digitised in order to generate a 12 segments model of the skier. R means right.

3.3.4.2 Reconstruction of 3D data

Although in DST as in running or walking most of the joint movements are taking place in the sagittal plane, a 3D kinematic analysis of the data was conducted in order to calculate the mechanical energy fluctuations occurring during the cycle. The rational for using 3D data develops from a technical characteristic of cross-country skiing. In contrast with beginners, expert skiers produce an accomplished lateral displacement of the body centre of mass over the supporting leg (S.N.M.F, 1999).

For condition 1 only (i.e. normal skiing speed, DSTn), the video recordings from the frontal camera were converted into a sequence of images to be digitised with the software Ka Video. The same points were digitised as reported in figure 3.6. Images from frontal and sagittal cameras were synchronised by using the right pole plant event. Using both cameras data, the program KaVideo allowed the 3D reconstruction of the coordinates of each joint. KaVideo software used a two-steps procedure to calculate the 3D coordinates from 2D video data. However, before 3D data can be determined, two "problems" must be solved which are related to the correction for scale of the image. First, this difference in scale can be attributed to differences in the camera distance to the subject and / or due to differences in the zoom setting on the camera lenses. Second, since the cameras were not genlocked, a phase shift between the two sets of data may occur. This phase difference can be attributed to lack of synchronization between the cameras and errors in defining the first frame for each data set. In KAVideo software, the correction for scale was made on the basis of a single magnification factor applied across all points in the side view. However, this scale correction strategy does not take into account the differences in scale caused by perspective in the front view data. Thus, the original front view data can be slightly distorted by the use of a single scale factor across the full range of motion. In order to get more accurate three dimensional data Ka Video software include a perspective correction procedure in the front view and side view data analysis. By mathematically analyzing the information provided by both of the cameras, it is possible to correct for perspective errors and determine undistorted 3D data from a two-camera video analysis (Black and Sprigings, 1974).

With regard to the calculation included in the program KA Video, one can report that Ka Video does not strictly generate of a 3D model of the skiers, as with the use of DLT and appropriate methods for describing position in 3D (i.e. matrix, Euler or screw methods). It is more a pseudo 3D analysis allowing a representation of the movement of the skier within a sagittal plane and a frontal plane.

3.3.4.3 Filtering process

The 2D joint position data were filtered using a Butterworth filter from the software BioProc2 (Robertson and Marcoux, 2002) that is reported as a software resource in the International Society of Biomechanics website. Following the determination of the cut-off frequency methods used and reported in the pilot study a selection of cut-off frequencies for the shoulder, elbow, hip, knee and ankle was made using data from one subject. The cut-off frequencies selected ranged between 5 and 6 Hz depending on the joints (i.e. 5 Hz for the hip, knee and elbow joints and 6 Hz for the shoulder and ankle joints). Similar procedure were used for the mechanical analysis were filtered using a 2nd order Butterworth low pass filter with the cut-off frequency ranging from 5 to 6 Hz.

3.3.4.4 Quantification of the digitising error on 2D data

As previously mentioned in the literature review, the manual digitising constituted a possible source of error. The error generated by the experimenter can influence the results in terms of both linear and angular kinematics. Assessment of these errors must be analysed in order to have of view of the precision of the chosen video analysis.

3.3.4.4.1 Digitising effect on linear displacement

The investigation of the effect of the manual digitalisation on the linear displacement was accomplished by comparing the lengths calculated by the software to the real lengths. The same experimenter repeatedly manually digitized 10 times the 2m reference length used for calibration. The results showed that for the three axes (horizontal, vertical and transversal), an error of 3.07 ± 0.6 %, thus a maximum error of 12.3 cm can be expected over a standard DST cycle of 4 meters.

3.3.4.4.2 Digitising effects on the angular joints.

The effect of the digitising process on the 2D joint angulation was investigated using data from one subject undertaking a normal speed DST (condition 1, DST_n).

- Context of the quantification of the maximum digitising error

The same sequence of 40 images of the DST representing a half-cycle (i.e. defined as two consecutive pole plants) from the right side of the wrist, elbow, shoulder, hip, knee and ankle joints were digitised 12 times by the same investigator. Using the Ka video software, the filtered (i.e. Butterworth filter with a cut-off frequency of 5 to 6 Hz) angular displacement of the elbow, shoulder, hip, knee and ankle joints was obtained for each image.

The estimation of the maximum digitising error depends on the number of digitisations undertaken and averaged to generate the data. The determination of the optimal number of digitisations to average was realised using smoothed data from the hip joint and the protocol that follows. For each image in the sequence, the hip angle was calculated. The difference between the maximal and the minimal angular values was then calculated using an average of 2, 3.....10, 11 or 12 digitisations. These were then averaged over the 40 sequence images. The results were reported in the figure 3.7. It showed an increase of the mean digitising error for up to 9 repeat digitisations but the values remained relatively stable for higher numbers of repetitions. (figure 3.7).

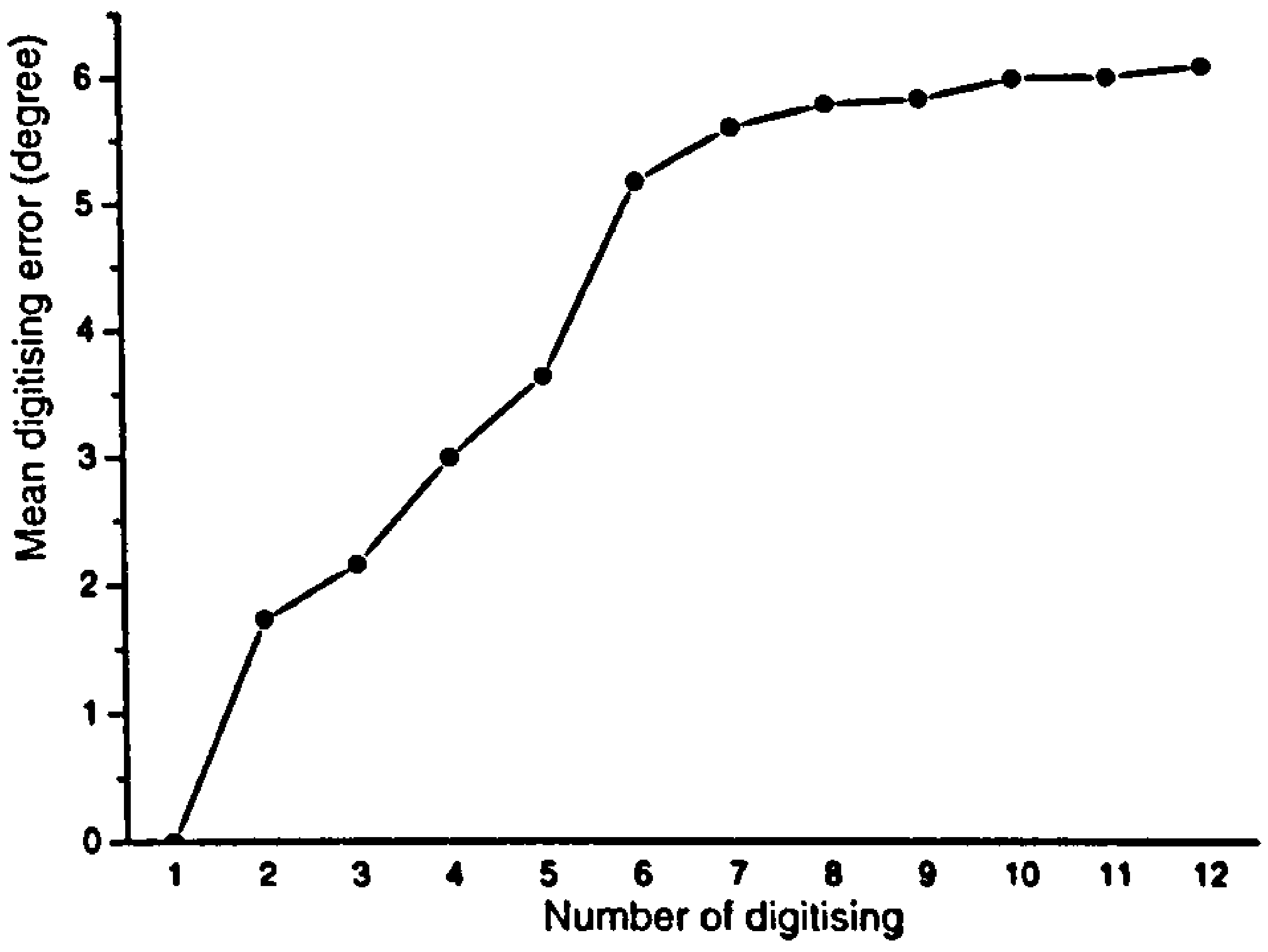


Figure 3.7: Evolution of the mean digitising error on the hip joint with the increasing number of repeated digitalisation of the same sequence of images.

Therefore, it was assumed that 12 digitalisations were enough to account for the maximum digitising error in the joint angulations, since a stabilised plateau in the mean digitising error was observed.

For all the joints, the same method as reported above was used with 12 digitalisations to calculate the mean digitising error.

- Results-digitising effects on the angular joint

The results showed a mean angular error of 5 to 7 degrees in the joints. The details are presented in table 3.5.

Table 3.5: Mean (± StD) digitising error (in degrees) observed in the elbow, shoulder, hip, knee and ankle. Values resulted from the 12 digitalisations of the same sets of data.

Joints	Error (°)
Elbow	7.0° ± 3.3
Shoulder	6.0° ± 2.7
Hip	5.5° ± 2.1
Knee	5.3° ± 1.65
Ankle	6.2° ± 2.8

Since the range of motion of the shoulder, hip and ankle is larger than for the knee, the digitising error may have more impact on the knee joint than on other joints. Overall, the error made in the digitising process is acceptable but may need to be kept in mind while discussing the kinematical and mechanical generalisation of the results.

3.3.4.5 Quantification of error on 3D data

Monteil et al., (1996) validated the Ka Video software showing good validity results with reference to optical systems. In addition, the "perspective correction" in the software Ka Video was evaluated in laboratory conditions by Schleihauf (2005). The determination of the XYZ coordinate of two rotational markers showed a measurement error of less than 0.5% of the length between the two points. Therefore, the scale and perspective mathematical corrections accommodate the error generated by the experimental set-up, the major amount of error affecting the 3D data developed from the digitising process. As previously reported, the characteristics of the Ka Video program suggest that the quantification of the errors in the 3D data may be mostly estimated as the digitising error on the linear and angular displacement.

3.3.5 Data analysis

Over the three trials recorded in DST_n (condition 1) and DST_{wp} (condition 3), for each subject the best trial was selected for analysis. This selection was made in order to respect 2 requirements: 1) an entire cycle (defined as the period between two consecutive lifts from the snow of the right ski) with a least 10 images before and after the images sequences, 2) no visible unbalance state or movement exaggeration from the skier.

The analysis of only one cycle was justified by the results of the pilot study (section 3.2). It showed that skiers produced reproducible joint movement patterns when undertaking the DST.

In the fast skiing condition DST_f(i.e. condition 2), we measured cycle lengths that were larger than expected from previous studies (Roy and Barbeau, 1991; Bilodeau et al., 1992; Nilsson et al., 2004) and preliminary study (section 3.2) it has been difficult to obtain a full cycle for each subjects. Therefore, the entire cycle was reproduced with the study of two trials each of them representing a half-cycle, one with a left leg propulsion phase, the other with a right leg propulsion phase. For each subject, the skiing speed of the analysed two trials was checked to be within a 5% difference threshold.

3.3.5.1 Temporal and spatial cycle analysis

3.3.5.1.1 Cycle decomposition

The literature review exposed the important discrepancies in the description of the phases in DST (section 2.3.1.2). In order to compare the DST data obtained in this study with other of human gaits, the cycle was divided into a swing phase and stance phase. The stance phase can additionally then be divided into support and propulsion phase because each has a different function in the cycle. The former allows the contralateral swing and propulsion phases; the latter allows the generation of leg forces (figure 3.8).

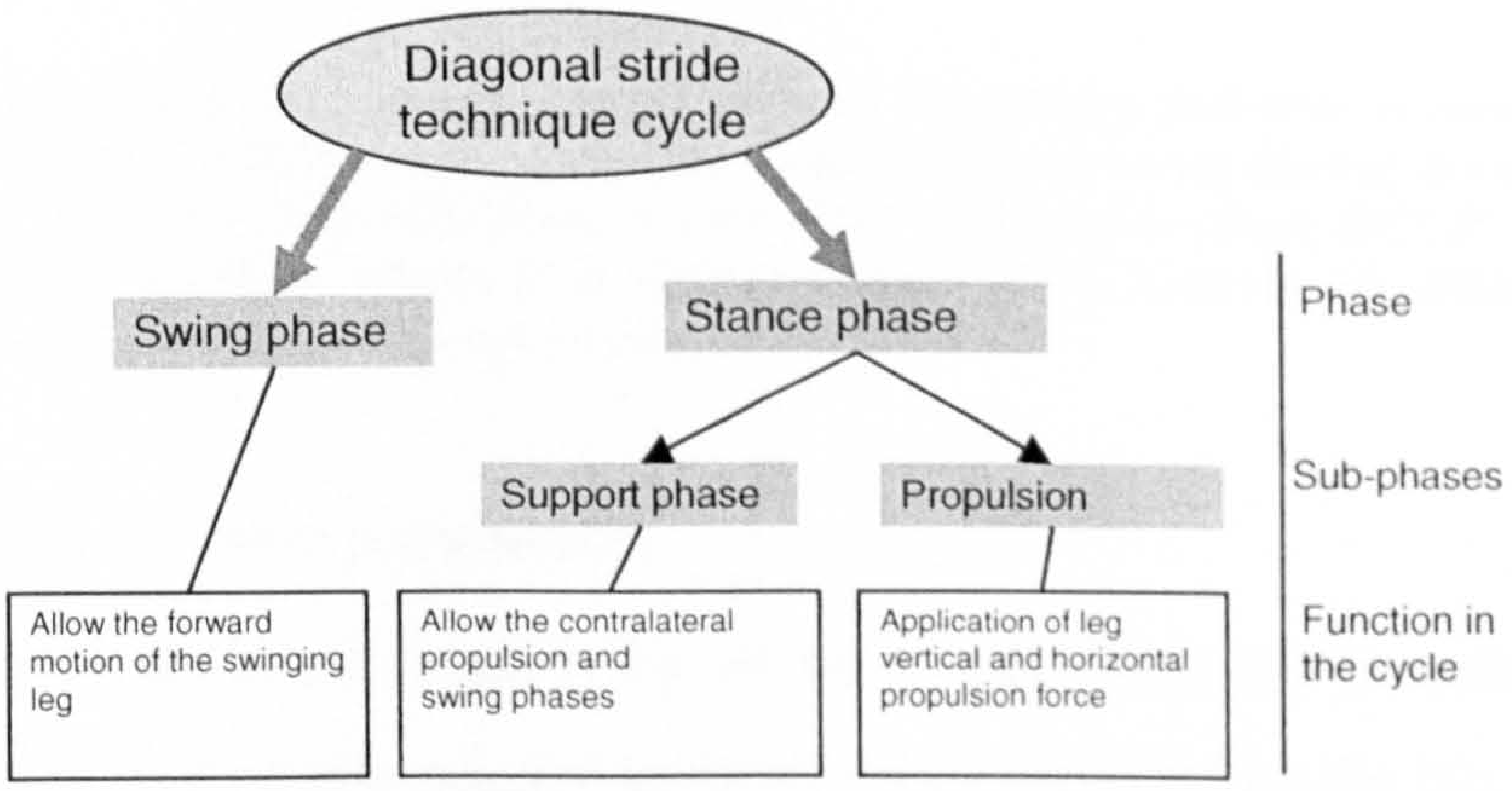


Figure 3.8: Decomposition of the leg DST cycle.

The swing phase corresponded to the moment the right ski lifts from the snow (figure 3.9, RSL1) until the feet remained adjacent (BCLP). The stance phase started at BCLP and ended when the right ski lifts from the snow for a second consecutive time (RSL2). In accordance with previous studies (Dillman et al., 1979; Bilodeau et al., 1992; Nilsson et al., 2004), the propulsion phase was defined as the moment the feet remained adjacent (BRLP) until RSL2.

The propulsion phase of the arms was defined as the moment the right tip pole touch the snow (RPP) until the tip pole lift from the snow (ERPP).

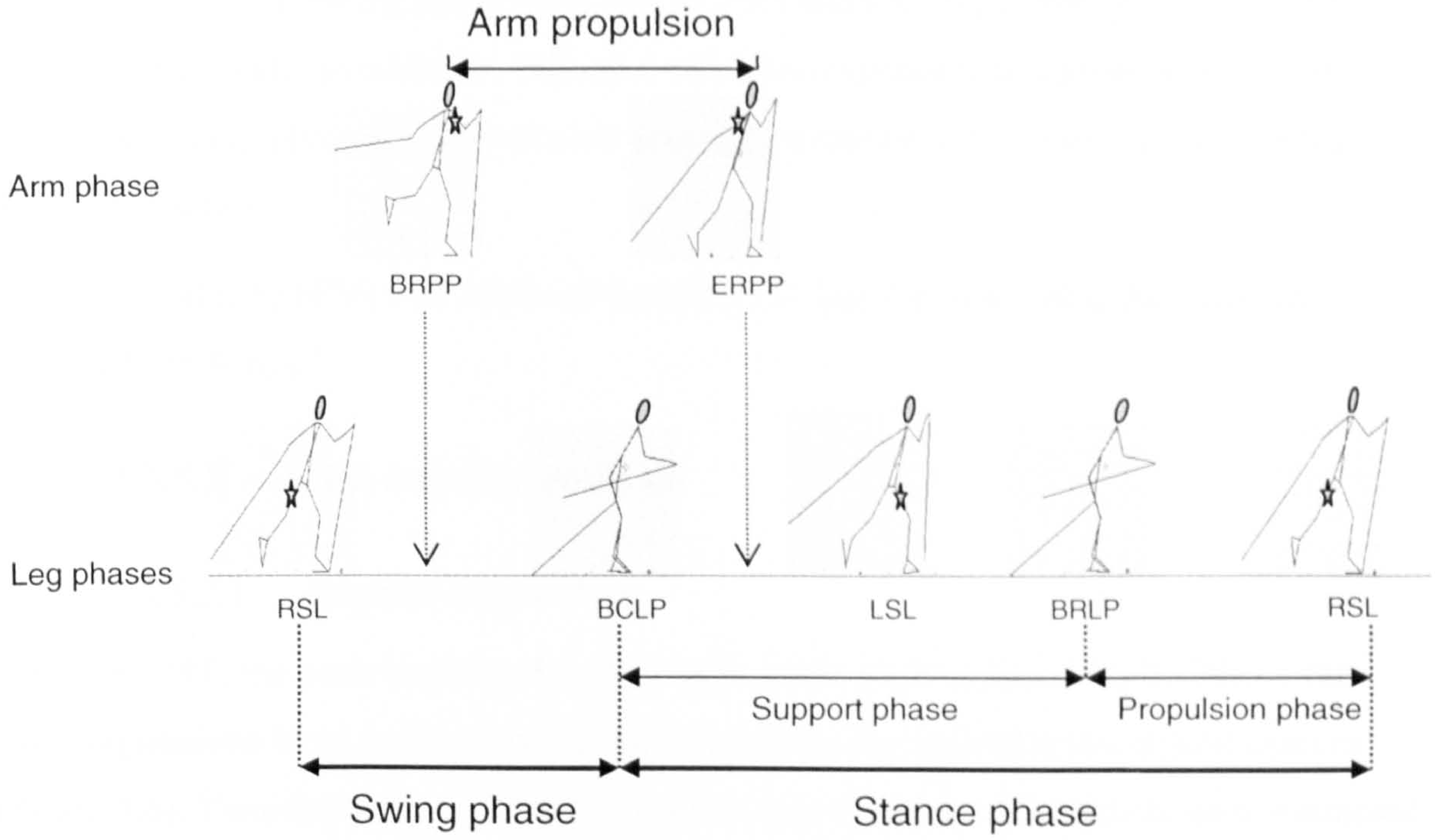


Figure 3.9: Determination of the diagonal stride cycle, leg phases and arm propulsion phase. Support phase corresponded to the supporting action of the right leg during the contralateral propulsion and swing leg. RSL1(2): Right ski lift; RPP: Right pole plant; BCLP: Beginning contralateral leg propulsion; ERPP: End right pole plant; LSL: Left ski lift; BRLP: Beginning right leg propulsion (Star indicates the right limb).

3.3.5.1.2 Cycle parameters

From each cycle, the cycle length (CL), swing length (SwL) and propulsion length (PL) were calculated. They corresponded to the distance travelled by the hip during the whole cycle (from RSL1 to RSL2), the swing phase (from RSL1 to BCLP) and the propulsion phase (from BRLP to RSL2) (figure 3.9). In condition 3, cycle length was calculated as the sum of the two half-cycle lengths.

Temporal cycle parameters were also extracted from the cycle. The cycle duration (CD) was calculated using the formula: $CD = 50 \times (n_i - 1)$ s, where 50 is the camera frame rate and n_i is the number of frame counted in a whole cycle (RSL1 to RSL2). For condition 3, n_i corresponded to the sum of the number of frame counted in both half-cycle. The cycle frequency (CF) was calculated as the inverse of CD: $CF = 1/CD$

Additional temporal cycle parameters were expressed as absolute or relative values. Absolute swing duration (SwD) and absolute propulsion duration (PD) corresponded to the durations of the swing phase (RSL1 to BCLP) and the propulsion phase (BRLP to RSL2) respectively. In addition, PD and SwD were expressed as a proportion of the cycle duration to give values of relative propulsion duration (PDr) and relative swing duration (SwDr).

The cycle velocity (CV) was obtained from the CL and CF, following the formula $\mathrm{CV} = \mathrm{CL} \times \mathrm{CF}$ $\mathrm{m \cdot s^{-1}}$.

3.3.5.2 Joint angular analysis

3.3.5.2.1 Angular convention

Since, in DST, the main angular changes occur in the sagittal plan (Smith, 2003), the joint angulations were analysed using data from only the sagittally positioned camera (figure 3.5). Two-dimensional elbow, shoulder, hip, knee and ankle joints were extracted from the Ka Video and filtered as previously described. Angles were then expressed as anatomical angles (Zatsiorsky, 1998). Elbow, hip and knee angles were defined with reference to the downward prolongation of the upper segment (figure 3.10). The shoulder angle was expressed in reference to the upward prolongation of the trunk. The ankle angle corresponded to the angle made between the line heel-toe and the forward perpendicular to the shank. Joint ankle in dorsiflexion constituted angles inferior to 90 degrees. Joint ankle in plantarflexion corresponds to angles superior to 90 degrees.

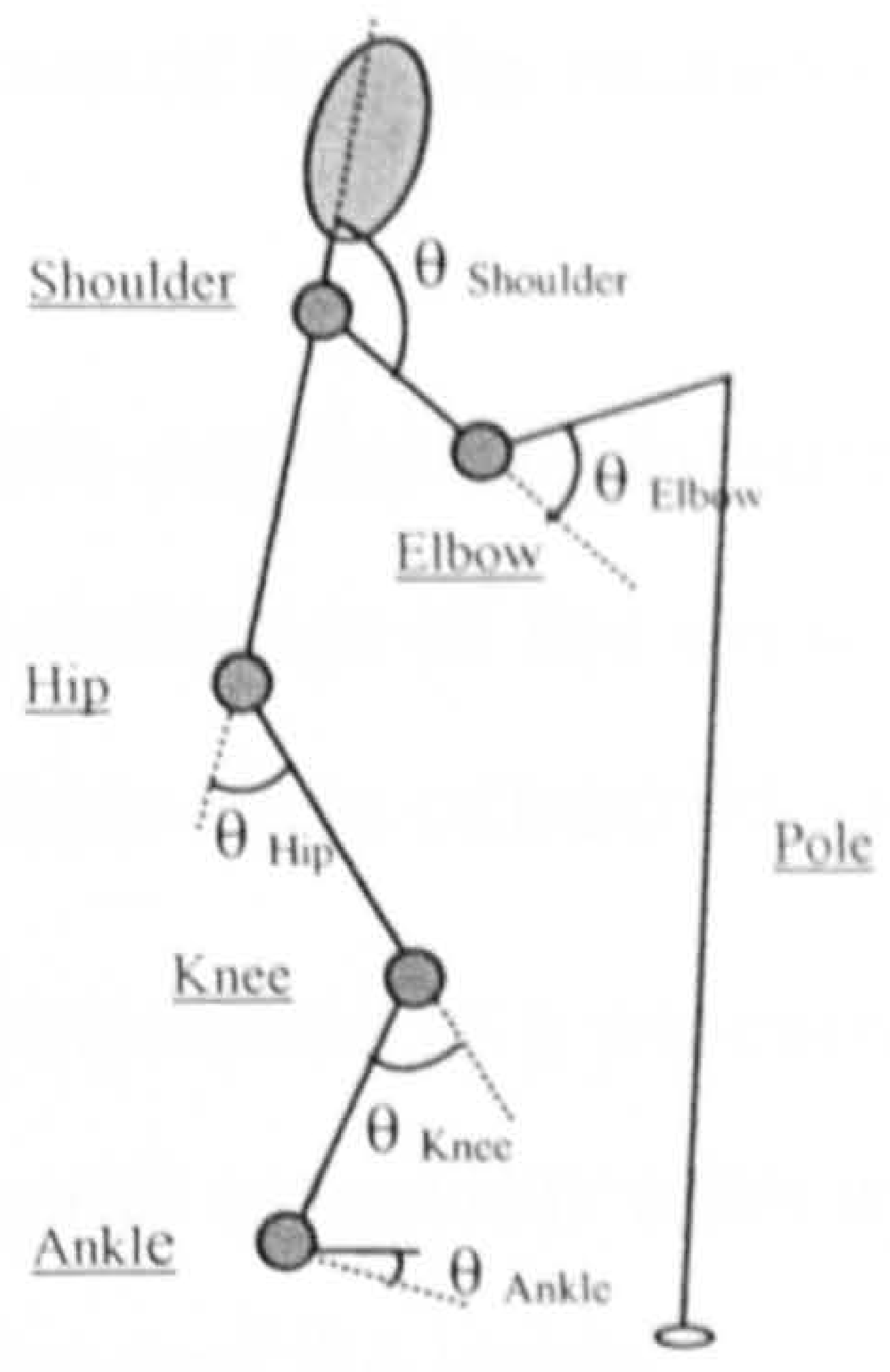


Figure 3.10: Angular convention used for the elbow, shoulder, hip, knee and ankle angles

From the joint angular displacement a first time finite difference differentiation was used to calculate joints angular velocity using the equation 4.3:

Equation 3.3: $\omega_{n+1} = \frac{\vartheta_{n+2} - \vartheta_n}{2\Delta t}$ **(Winter, 1990)** ϑ_{n+2}

where ω_{n+1} is the angular velocity at the n+1; ϑ_{n+2} and ϑ_n are the angular displacement at time n+2 and time n; $2\Delta t$ represents the time between two adjacent samples ϑ_{n+1} and ϑ_n (i.e. 0.02 second for a 50 rate sampling).

Joint angular displacement and velocity data from condition 1 and 3, were reduced to a full cycle and time normalised to 101 points with a spline procedure using the software BioProc2 (Robertson and Marcoux, 2002).

3.3.5.2.2 Joint angular parameters

For each joint a mean displacement and velocity pattern was generated from the 8 subjects. The principal joint angular parameters extracted were:

1- Mean range of motion (ROM) of the hip, knee and ankle of the lower limb were determined for the entire cycle, for the swing phase and for the stance phase (figure 3.9). Similarly mean ROM of the shoulder and elbow were determined during the arm propulsion phase (figure 3.9). The ROMs were defined as the difference between the maximal and the minimal angular values observed in the phases.

2- From the hip, knee and ankle angular displacement patterns; the amplitude and temporal (expressed as a percentage of the cycle) values of the characteristical peaks of flexion and extension were extracted and averaged.

3- The spatial and temporal (expressed as a percentage of the cycle) values of the most characteristic flexion and extension velocity peaks were extracted and average for the hip, the knee and the ankle.

Parameters 2 and 3 were detailed in Study 1 (section 4.1) and used for analysis in studies 1, 3 and 4 (section 4.1, 4.3 and 4.4).

3.3.5.3 Mechanical energy and work analysis

The measurement and calculation of the mechanical energy expenditure and work done in human motion were realised using the approach of the *centre of mass model* (Zatsiorski, 2002). This method was developed by Cavagna and Kaneko (1977), modified by Minetti et al. (1993) and validated by Willems et al. (1995).

3.3.5.3.1 Mechanical Energies

Despite legged locomotion being the result of the coordinated actions of dozens of muscles that produced the movement of the body segments, each gait can be described by a simple model which helps understanding the overall mechanics of the progression along the ground. More specifically, the models determine for each gait the interplay among the three energies associated to the body centre of mass (BCM), namely the potential energy (E_P, $m \cdot g \cdot h$), the kinetic energy (E_K, $0.5\ m \cdot v^2$), and the elastic energy (E_L), where g is acceleration due to gravity (9.81 $m \cdot s^{-2}$), m is the mass in kilograms, h is the vertical coordinate above an arbitrary level (meters)and v is the speed ($m.s^{-1}$) of the body centre of mass (Saibene and Minetti, 2003). The interplay of the 3 mentioned energies of the BCM allowed the description of walking and running gaits.

Walking has been classically described by the inverted pendulum / rolling egg model (Margaria, 1976). In those models, E_P and E_K continuously exchange, resulting in a total mechanical energy (i.e. sum of E_P and E_K) with small fluctuations over the stride. This mechanism minimises the net energy needed to sustain the motion of the system. The ability to save mechanical energy by using a pendulum-like model can be quantified using the so-called energy recovery parameter (Cavagna and Kaneko, 1977).

Running has been classically described as a bouncing ball/pogo stick models (Margaria, 1976). In contrast to walking, E_P and E_K change in phase during the stride. In this gait EL has a crucial role in exchanging with the sum of the other two energy types.

3.3.5.3.2 Mechanical work

The mechanical energy changes (i.e. the work) required to maintain the overall motion have received considerable attention because they potentially affect the metabolic expenditure (Fenn, 1930; Cavagna and Kaneko, 1977; Minetti et al., 1993, 1995; Willems et al., 1995; Saibene and Minetti, 2003). In the centre of mass approach, the kinetic energy of the human body is represented as the sum of the energy associated with motion of the BCM and the energy associated with motion of individual segments relative to the BCM.

The work done to raise and accelerate the BCM within the environment and the work associated with the acceleration of the body segments are called the external work (Wext) and the internal work (Wint) respectively. Wext and Wint are calculated using equations 3.4 and 3.5:

Equation 3.4: $Wext = \Delta E_{TOT}$

With $E_{TOT} = E_{KXcg} + E_{KYcg} + E_{Pcg}$

Where ΔE_{TOT} represents the change in the total energy of the body centre of mass; E_{KXcg}, E_{KYcg} and E_{Pcg} correspond to the horizontal kinetic energy, vertical kinetic energy and potential energy of the BCM respectively.

Equation 3.5: $W\text{int} = \Delta E_K$

with $E_K = E_{Kt} + E_{Kr}$

Where ΔE_K is the change in the kinetic energy of the centre of mass segments relative to BCM; E_{Kt} is the translation kinetic energy of the segment centre of mass relative to BCM; E_{Kr} is the rotational kinetic energy of the segment centre of mass relative to the body centre of mass.

The total work (W_{TOT}) of locomotion has been classically regarded as the sum of the Wext and Wint (Cavagna and Kaneko, 1977) (equation 3.6). This resulted from the an interpretation of König theorem of mechanics stating that the overall E_K of the centre of a linked multi-segment system is the sum of the E_K of the centre of mass of the system and those of the segments, calculated from their relative speeds from the centre of mass of the system. The first component has been assimilated to be the Wext and the second to be the Wint.

Equation 3.6: $W_{TOT} = Wext + W\text{int}$

where W_{TOT}, Wext and Wint represent the total work, the internal work and the external work respectively.

An important mechanical parameter, already mentioned above is the *percentage recovery* introduced by Cavagna et al. (1976). The parameter reflects the ability of a multi-segment system to save mechanical energy through a pendulum-like mechanism, was calculated from the potential and kinetic energies of the body centre of mass.

It is calculated:

Equation 3.7: $re\operatorname{cov}ery(\%) = 100 \times \frac{W_H + W_V - Wext}{W_F + W_V}$

where W_H and W_V are the summation, over the stride of all the increases in horizontal (E_H) and vertical energies (E_V) respectively. The E_H and E_V are defined as:

$E_V(t) = E_P(t) + E_{KY}$ and $E_H(t) = +E_{KX}(t)$

3.3.5.3.3 Computation of the mechanical work

Each segment mass, centre of mass position and radius of gyration were taken from standard anthropometric tables (Demspter et al., 1959). As reported for the calculation of the 2D BCM, the poles and skis were neglected in the computation of the internal and external mechanical work. As in the method reported by Minetti et al. (1993), the data referred to 3D, two-sided coordinate system; The head and trunk segment is included in as a separate moving part in the calculation of the internal work; the reference point for calculation of segment relative speeds is here the true body centre of mass, obtained by the position of all 12 body segments (figure 3.6); the translational and rotational kinetic energies of adjacent limb segments were added together, allowing for a within-limb energy transfer.

The raw 3D coordinates of all points digitised over a full DST cycle were exported from Ka Video. The 3D displacements of the segments centre of mass and BCM were calculated for each frame from the position of the 12 segments using a custom programme (Minetti and Consani, 1989) created using Lab View 2/Macintosh (National Instruments, Austin, TX, USA) (Minetti, et al 1993). From the 3D trajectories, the programme calculated the biomechanical parameters.

3.3.6 Statistical analysis

The selection of appropriate tests (i.e parametric or non parametric) has to be done in reference to the properties of data (Field, 2000). All parametric tests have four basic assumptions that must be met for the test to be accurate. They are: 1) normally distributed data, 2) homogeneity of variance, 2) interval data and 3) data from different subjects are independent. In our data, all four assumptions for using a parametric test were not respected.

The normal distribution was tested using Kolmogorov-Smirnov test. The distributions tested were different from a normal distribution. Also the small number of subjects tested justified that we opted for non parametric tests (i.e. Wilcoxon and Mann-Whitney tests). This will have some consequence on the conclusions drawn since non-parametric tests are less powerful than parametric tests. There is an increased chance of a type II error (i.e. more chance of accepting that there is no difference between groups when, in reality, a difference exists).

The investigation of the differences in the biomechanical parameters between the different conditions was undertaken using non-parametric related test (Wilcoxon) and/or independent test (Mann-Whitney). A significant level of $p<0.05$ was chosen.

CHAPTER 4. RESULTS

4.1 Study one: Kinematic description in the DST movement strategies

4.1.1 Rationale

As discussed in the literature review (2.1.2.4), this study flowed from the lack of data in the literature to document the joint angular patterns in the DST. This kind of analysis is indeed important because it constitutes a basis of data that will allow 1) a better understanding of the strategies used to progress along the ground in the DST and 2) the development of further studies. Therefore, study 1 aims to provide a complete kinematic description of the DST movement.

4.1.2 Introduction

Kinematic investigations are a commonly used method for analysing human motion (Winter, 1990). Results of kinematics studies demonstrated that a motor task requires a specific movement pattern and a specific underlying coordination (Stallings, 1982). Many researchers have been interested in describing human locomotion because it represents a vital means of transportation. Numerous studies have analysed the temporal patterns and the kinematics of walking and running in order to understand the segmental strategies for generating the resulting displacement (Murray, 1967; Mann and Hagy, 1980; Nilsson et al., 1985). As developed in the literature review, the DST constitutes another human locomotion mode that has been used for over a thousand years, but in contrast to walking and running involves gliding and the use of skis and poles. One can assume that the DST constituted a particular motor task that will require specific movement patterns for generating the required displacement. Whereas the spatial and temporal patterns of the cycle have been used to discriminate skiers of different performance level (Marino et al., 1980; Bilodeau et al., 1996) data relative to the kinematics of the DST remain very limited, dealing with a small number of subjects and/or a small number of joints tested (Gagnon, 1981; Komi et al., 1982; Komi and Norman, 1987).

Therefore, to date, a detailed kinematic description of the DST remained to be done. In regard to the kinematics of walking and running, it was proposed that the analysis of the DST would reflect the segmental organisation related to the specificities of the locomotion. In addition, analysing the DST will constitute a basis for completing our understanding of the functions of the lower and upper body joints during a gait cycle. It will also constitute a basis for further kinematic analyses on the DST.

The purpose of this study was to analysis the DST motor task through the description of movement strategies which generate locomotor displacement with specific reference to walking and running. The angular time course of the lower and upper body joints were analysed spatially and temporally for each phase in the cycle.

4.1.3 Methods

The subjects, the equipment, protocol and data treatment used were as reported in chapter 3 (section 3.3). In this study, the kinematic description of the DST was achieved using data from condition 1 (i.e. skiing speed for a normal training pace, DST_n) of the protocol (Chapter 3, section 3.3.3).

4.1.3.1 Data Analysis

The cycle velocity, cycle length, cycle frequency and relative swing and stance phase durations (i.e. estimation of swing and propulsion phase as a proportion of the entire cycle) were calculated as reported in chapter 3 (section 3.3.5.1.2)

The time-normalised shoulder, elbow, hip, knee and ankle angular displacement and angular velocity patterns over the entire cycle were obtained using the angular convention described in chapter 3 (section 3.3.5.2)

The mean range of motion (ROM) of the hip, knee and ankle were calculated from the swing and stance phases as reported in chapter 3 (section 3.3.5.2). Similarly, the mean ROM of the shoulder and elbow was calculated over the arm propulsion phase.

As reported in chapter 3 (section 3.3.5.2), the mean temporal and spatial angular displacement peaks and angular velocity peaks were analysed for all joints.

4.1.3.2 Statistical analysis

Mean (± StD) was calculated for each parameter. The occurrence of the joint angular velocity peaks were compared between joints using a non parametric Mann Whitney statistical test with a significant level of $p < 0.05$ as justified in the chapter 3 (section 3.3.6).

4.1.4 Results

Data from condition 1 that simulated a training velocity produced a mean cycle velocity of 4.04 ± 0.34 $m \cdot s^{-1}$, with cycle length and cycle frequency of 6.03 ± 0.76 m and 0.67 ± 0.03 Hz respectively.

4.1.4.1 Structure of the DST

The stance phase in the DST can be schematically represented by Figure 4.1. The foot was in contact with the ground for an average of 63% percent of the cycle. The leg was swinging for an average of 37 % of the cycle. Simultaneous propulsion using the arm and leg occurred for a total of 16% of the cycle. The DST is constituted of alternated phases of single, double and triple supports.

In walking, the contact phase and the swing phase represented 60 % and 40 % of the cycle respectively. In contrast, in running the support phase occurred during 40% of the cycle whereas the swing phase represented 60% of the cycle.

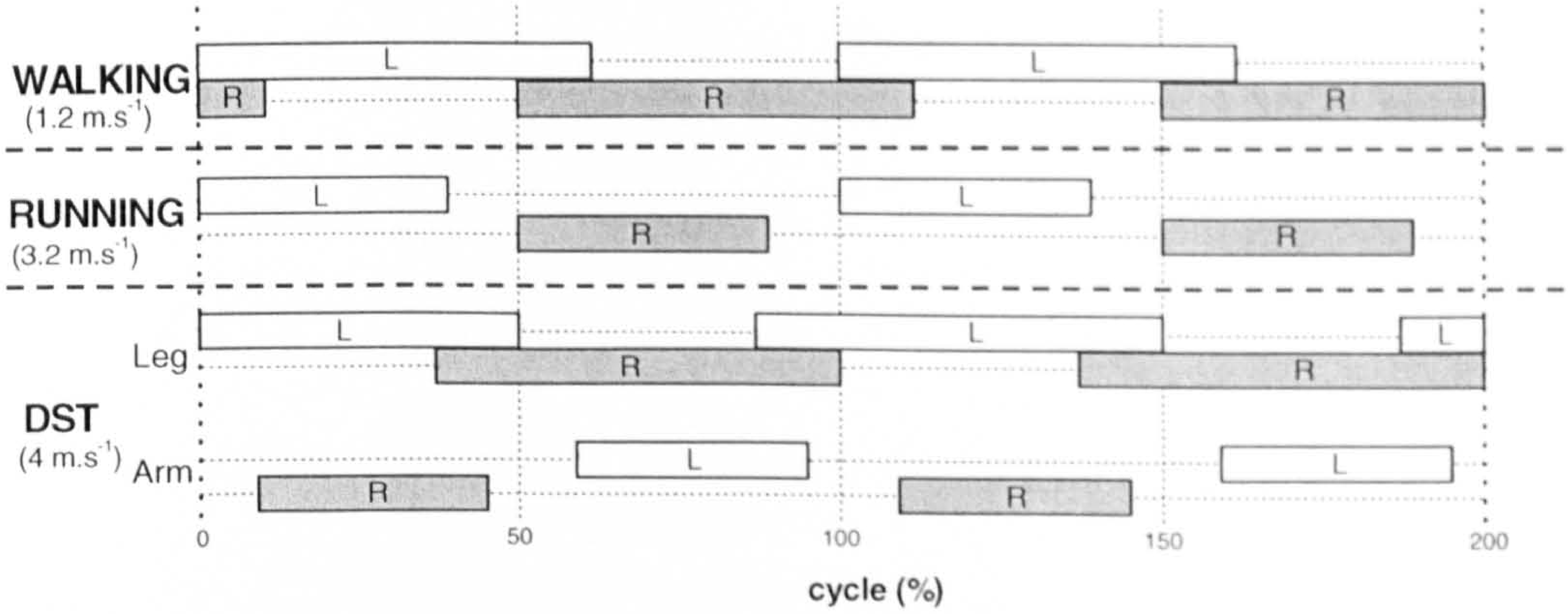


Figure 4.1: Typical contact patterns for walking, running and the DST. L and R refer to left and right leg, respectively; in the DST, the phase durations (leg support and swing phases and arm propulsion phase) were averaged from 8 subjects; walking and running percentage of support phase were reproduced from Novacheck (1998).

4.1.4.2 Lower limb

In order to facilitate the characterisation of the DST locomotion with reference to human gaits, kinematic patterns of walking and running (Novacheck, 1998) were displayed aside our data. The data was chosen from a review article from Novacheck which reported representative kinematic patterns of walking and running.

From the angular patterns of the lower limb joints, the main characteristics of the curves were extracted for further analysis as it can be seen in figures 4.2 and 4.3.

Considering the joint angular displacement patterns (figure 4.2) the main characteristics selected were:

- Hip extension peaks (HE1 and HE2) and hip flexion peaks (HF1 and HF2),
- Knee extension peak (KE) and knee flexion peaks (KF1 and KF2),
- Ankle dorsiflexion (AD).

4.1.4.2.1 Joint angular patterns

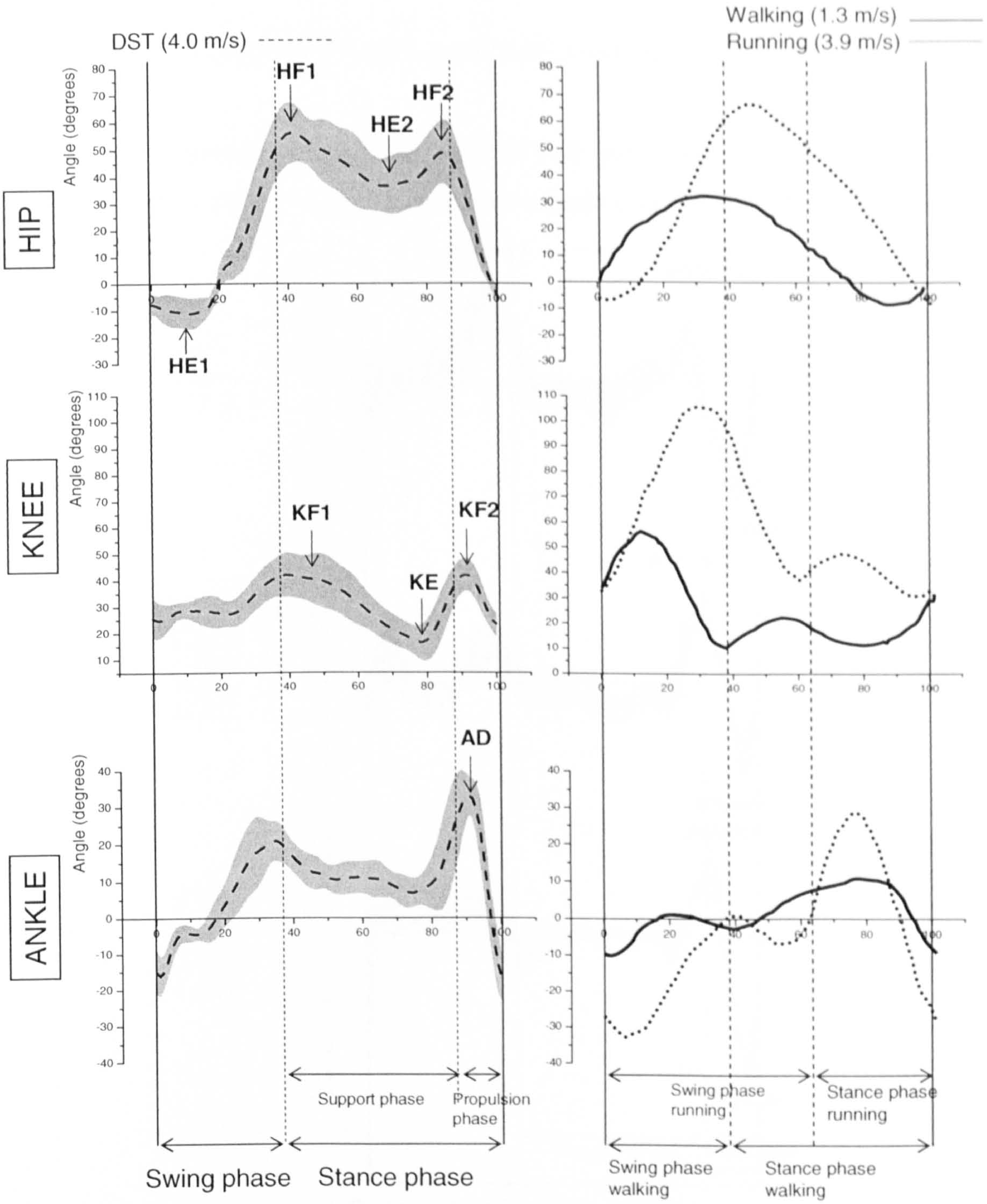


Figure 4.2: Hip, knee and ankle angular displacement observed in the DST and reported in walking and running (from Novacheck, 1998) during a full cycle. The cycle was defined as two consecutive right toe lift from the ground and expressed in percent. HF1, HF2, HE1 and HE2 represent the main characteristic of flexion and extension characteristics of the hip pattern. KF1, KF2, KE represent the main characteristic of flexion and extension characteristics of the knee pattern. AD represents the maximal dorsiflexion of the ankle.

Considering the joint angular velocity patterns (figure 4.3) the main characteristics extracted were:

- Hip velocity flexion peaks (HVelF1 and HVelF2) and hip velocity extension peak (HVelE),
- Knee velocity flexion and extension peaks (KVelF and KVelE respectively),
- Ankle velocity dorsiflexion and plantarflexion peaks (AVelD and AVelP respectively.

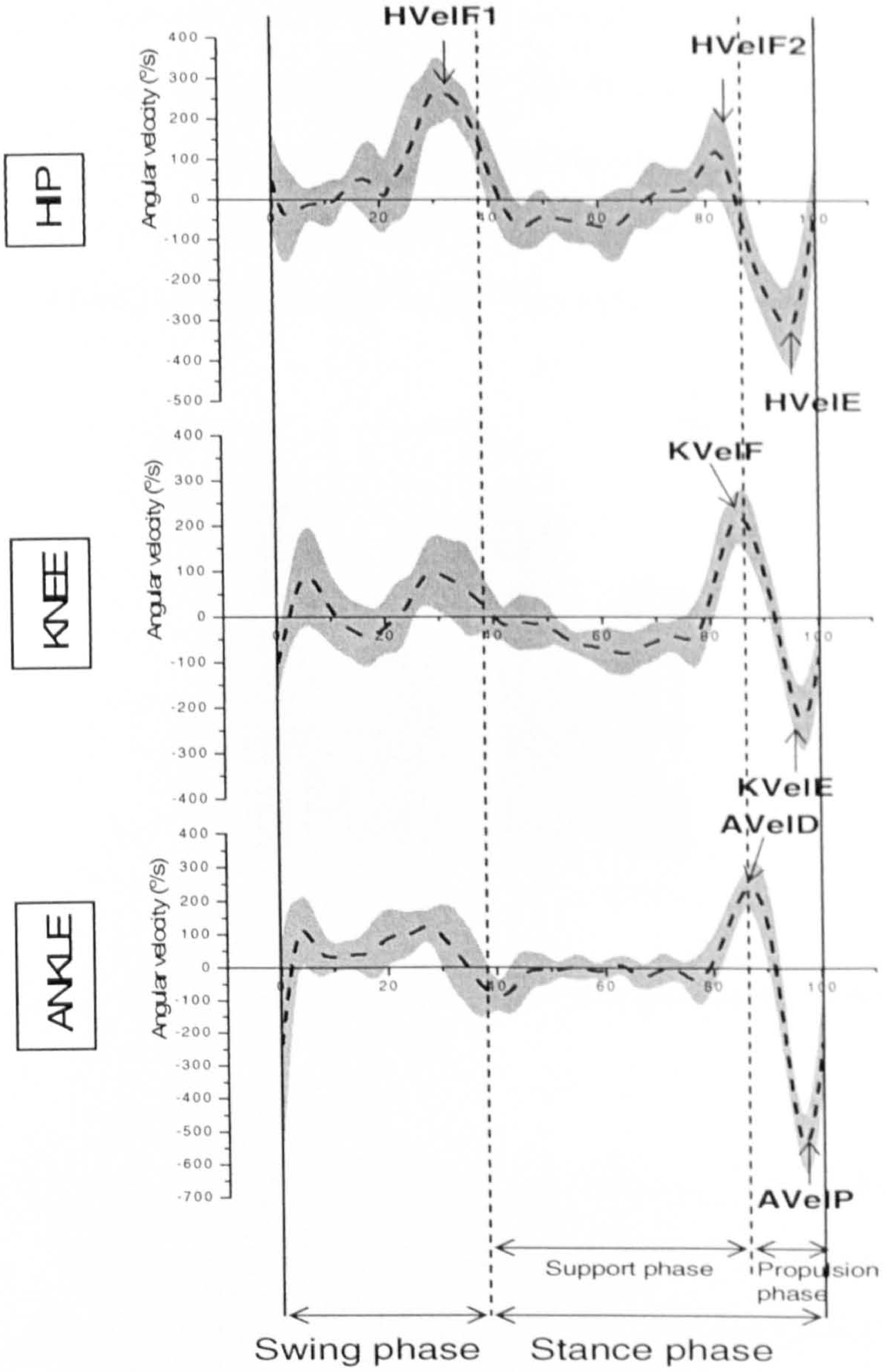


Figure 4.3: Hip, knee and ankle angular velocity patterns observed in the DST during a full cycle. HVelF1, HVelF2 and HVelE correspond to the two peaks of hip velocity flexion and peak of velocity extension respectively. KVelF and KvelE represent the peaks of knee velocity flexion and extension. AVelP and AVelD correspond to the peaks of ankle velocity dorsiflexion and plantarflexion.

4.1.4.2.2 Cycle

For the entire cycle, the range of motion (ROM) for the hip, knee, ankle was 66.9°± 8.2, 28.5°± 4.1 and 49.7°± 6.3 respectively.

4.1.4.2.3 Swing phase

During the swing phase, the hip underwent most angular displacement with an average ROM of 66.9° ± 8.2 whereas the ROM of the knee and the ankle were smaller with 23.9° ± 3.8 and 39.5° ± 3.8 respectively (Figure 4.4). The hip was characterised by a hyper-extension of 12.1° ± 5.3 (Figure 4.3, HE1) before beginning its flexion movement. This hip flexion phase was characterised by a large peak of flexion velocity (307°·s^{-1}± 66) occurring during the second half of the swing phase (figure 4.3, HVelF1).

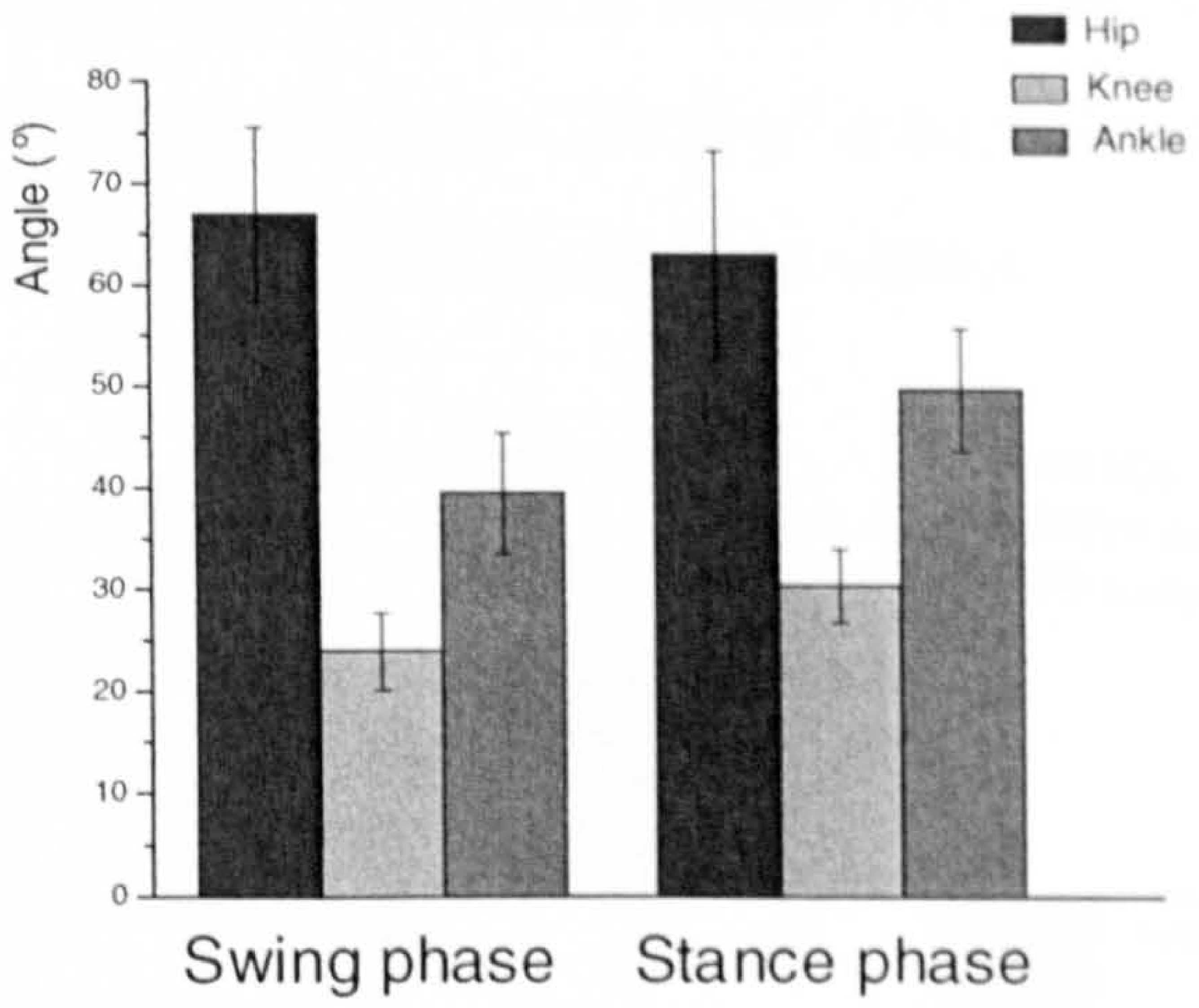


Figure 4.4: Range of motion of the hip, knee and ankle during swing and stance phases.

4.1.4.2.4 Stance phase

During the stance phase, the angular amplitude of the hip and the ankle (62.9° ± 10.2 and 49.6° ± 6.3) was larger in comparison to the knee joint (30.4°± 3.6) (figure 4.4).

The first part of the stance phase was characterised by hip and knee peaks of flexion (HF1 and KF1). During the second part of the stance phase, the hip and knee showed a small extension phases (HE2 and KE) whereas the ankle remained fixed in dorsiflexion (figure 4.2).

Occurring during or just prior to the propulsion phase; each joint showed a flexion motion prior to an extension phase (Figure 4.2 and 4.3).

Temporally the hip flexion velocity peak (HVelF) occurred prior to the knee (KVelF) and the ankle (AVelD) flexion velocity peaks (p=0.003 with 79.9 % ± 4.4 and 85.2 % ± 2.1; p=0.000 with 79.9 % ± 4.4 and 86.9 % ± 2.1) (figure 4.5). Similarly, the occurrence of hip extension velocity peak (HvelE) was significantly prior to the knee (KVelE) and ankle (AVelP) extension velocity peaks (p=0.021 with 94.9 % ± 2.0 and 96.8 % ± 0.9; p=0.028 with 94.9 % ± 2.0 and 96.8 % ± 0.7). In other hand, KVelF2 and AVelD, KVelE and AVelP appeared temporally coupled (p=0.105; p=0.878) (figure 4.5). The hip joint began the flexion at approximately 150 ms before the knee and ankle joint flexion. In contrast, the hip joint started the extension only 50 ms before the knee and the ankle joint extension.

Values of HvelF2, KVelF and AVelD were similar between the joints with 307 $^{\circ}\cdot s^{-1}$ ± 65.9, 242.3 $^{\circ}\cdot s^{-1}$ ± 51.0 and 261.0 $^{\circ}\cdot s^{-1}$ ± 51.9. AvelP with 546$^{\circ}\cdot s^{-1}$ ± 81.6, was larger than HVelE with -335$^{\circ}\cdot s^{-1}$ ± 79.5 and KVelE -230.8$^{\circ}\cdot s^{-1}$ ± 64.8. AvelP represented the approximating sum of HVelE and KVelE absolute values.

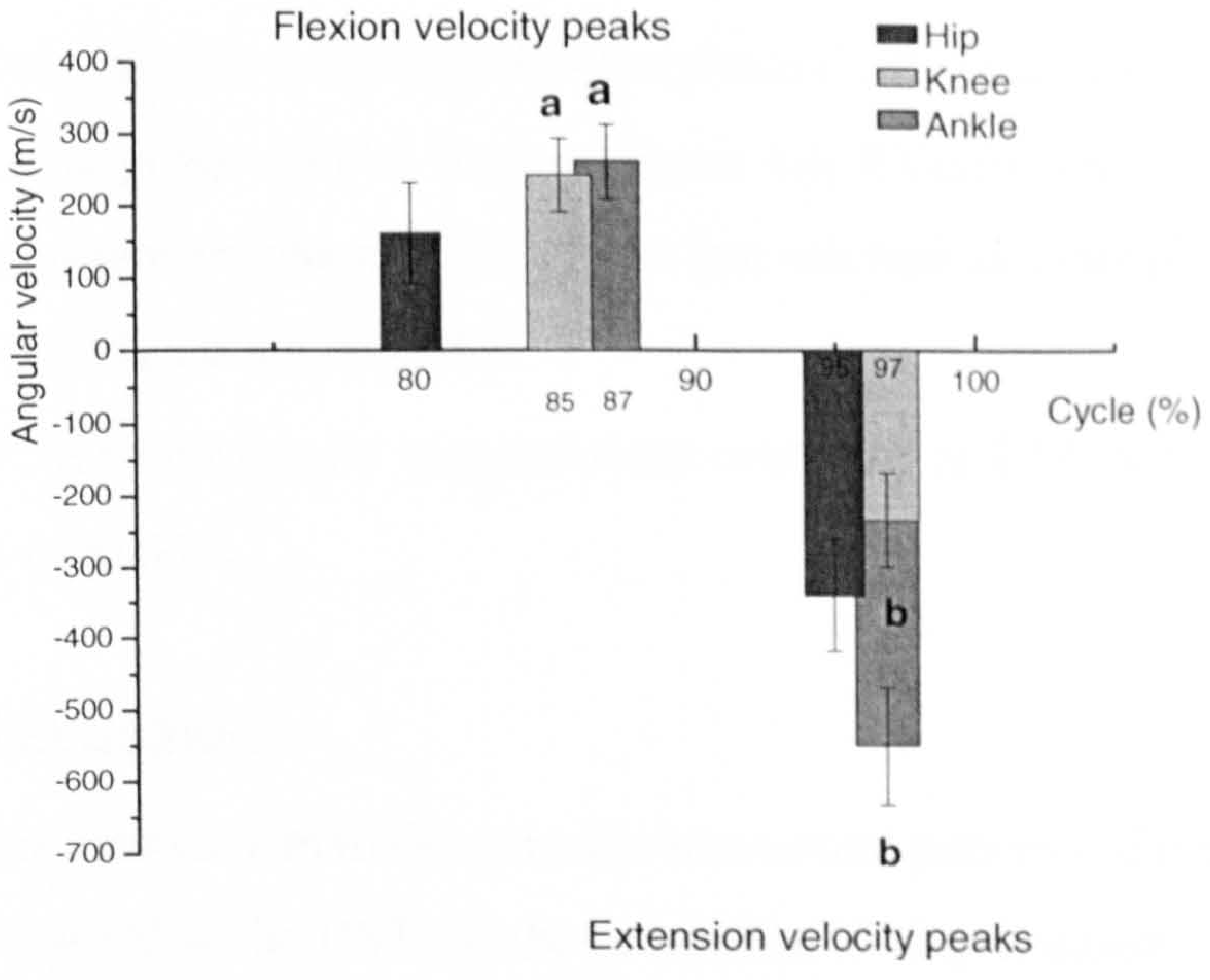


Figure 4.5: Occurrence in the cycle and value of the hip, knee and ankle angular velocity peaks; a represents a significant difference (p< 0.05) between hip and knee angular flexion and between the hip and the ankle dorsiflexion; b represents a significant difference (p< 0.05) between hip and knee and between hip and ankle peak angular extension.

4.1.4.3 Upper body

During the arm propulsion phase, the ROM of the shoulder and the elbow were reported to be 107.3° ± 8.7 and 76.6° ± 11.6 respectively. The shoulder angular motion was characterised by an extension phase during the whole of arm propulsion. Peak angular velocity extension of the shoulder (-285 $^{\circ}\cdot s^{-1}$ ± 81.7) was reported soon after the pole plant (figure 4.6, SVelE).

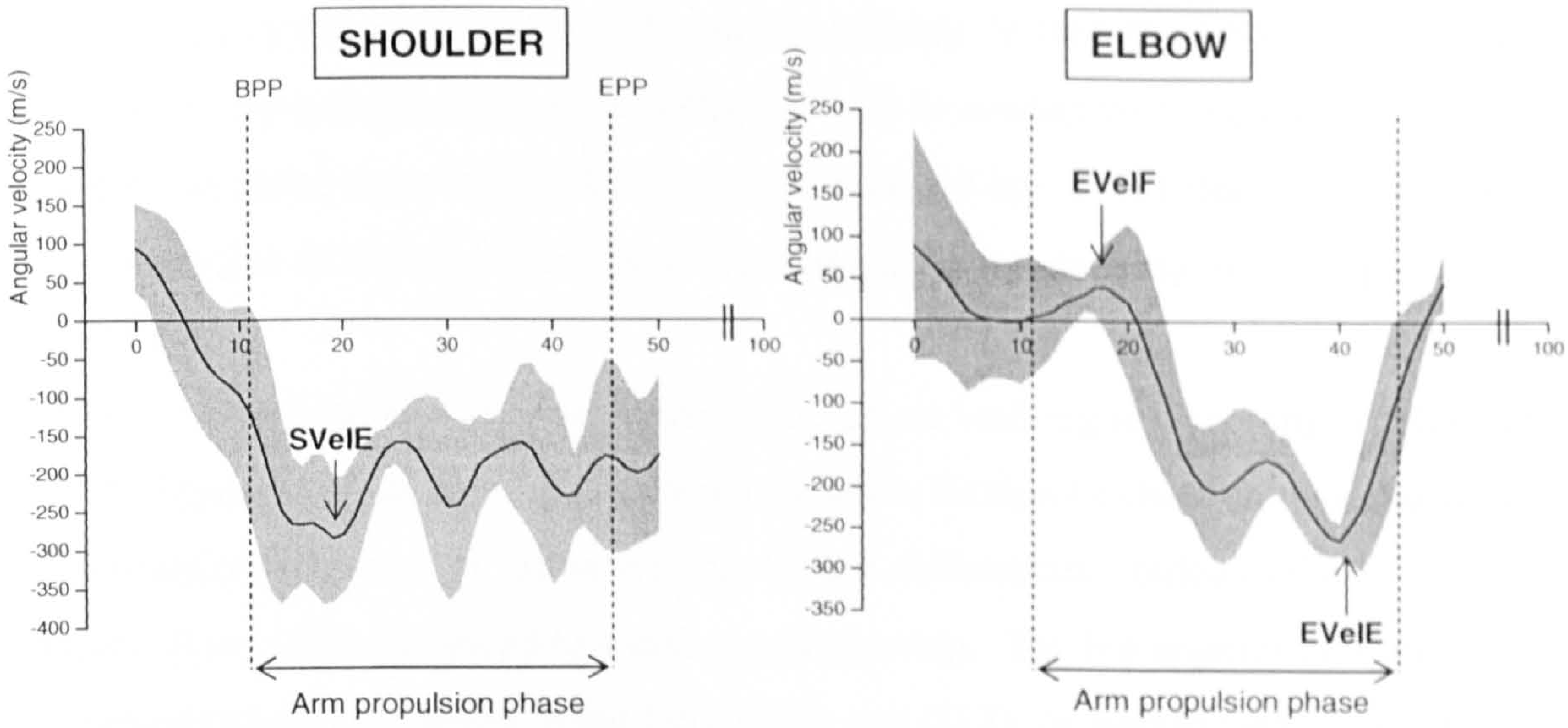


Figure 4.6: Angular velocity patterns of the shoulder and elbow during a full arm propulsion phase. BPP=Beginning Pole Plant, EPP=End pole plant.

The elbow was characterised by a slight flexion phase (7.2° ± 4.0) soon after the pole plant, and a peak of angular velocity flexion (figure 4.6, EVelF). This elbow flexion phase preceded an extension phase of the elbow that reached an extension velocity peak of -274.3 $^{\circ}\cdot s^{-1}$ ± 19.5 (figure 4.6, EVelE).

SVelE and EVelF were temporally coupled since occurring at 19.4 % ± 1.9 and 18.5 % ± 1.2 of the cycle ($p=0.645$).

4.1.5 Discussion

The purpose of this chapter was to describe the movement patterns of the upper and lower segments required in the DST for the generation of displacement.

Cycle velocity, cycle length and cycle frequency were consistent with previous work, that used a similar protocol (e.g. Roy and Barbeau, 1991; Nilsson et al. 2004). Previous authors considered the speed tested in this chapter as a medium speed for national level skiers, therefore validating our protocol for a speed sustainable over a training period. The total range of motion reported in this chapter for the hip and knee was consistent with previous work on the DST (Gagnon, 1981; Komi et al., 1982; Komi and Norman, 1987).

The percentage of support phase in the cycle has been reported as an external parameter to have an important impact on the mechanics and energetics of human and animal locomotions (Alexander and Jayes, 1980). Figure 4.1 showed the DST proportion of stance phase during the cycle to be analogous to walking. In both the DST and walking the locomotion showed periods where both legs were in contact with the ground. The arm propulsion phase acted in parallel to the contralateral leg. This behaviour is similar to the organisation of limb movements of quadrupeds during walking or trotting (Minetti, 1998).

The DST was shown to be a cyclical locomotion, as are walking and running (Grillner et al., 1979). A pattern of alternating hip, knee and ankle flexion / extension was observed in all locomotion (figure 4.2). However, significant differences resided in the kinematics of the DST compared to walking and running. The hip angular motion demonstrated two flexion peaks in the DST (HF1 and HF2). In walking and running, only one maximum hip flexion occurs in the cycle. This difference resulted from the technique used in the DST where twice in the cycle the legs were regrouped and flexed to prepare for the leg propulsions. In contrast to the hip patterns, the shape of the angular pattern of the knee in the DST was quite similar to that of walking and running. Nilsson et al. (1985) pointed out the ankle as the main joint differentiating walking from running. In the DST, the ankle angular curve showed more resemblance with running than walking (figure 4.2).

In order to shed light on the angular characteristics of the DST locomotion, the functions of the different joints within the cycle were analysed and referred to walking and running gaits.

4.1.5.1 Lower limb

4.1.5.1.1 Swing phase

During the swing phase, the lower limb kinematic joint patterns, showed differences and similarities to walking and running.

The amplitude of the hip angle in the DST was larger than in walking (Murray, 1967; Mann and Hagy, 1980) but rather similar to running (Mann and Hagy, 1980; Milliron and Cavanagh, 1990, Novachek, 1998) (for speed of 3.5-3.9 $m.s^{-1}$). Running showed a rather larger hip flexion compared to the DST but the DST featured a further hip extension at the beginning of the swing phase (figure 4.1; HE1). In walking and running, the toe-off lead to an instant hip flexion bringing forward the swinging leg (Mann and Hagy, 1980). In the DST, the elevation of the leg is a specific feature that may result from the acceleration of the trunk and upper arm (from previous leg propulsion) pulling the leg off the snow, as proposed by Van Ingen Schenau (1989) in jumping.

The amplitude of the knee during the swing phase was markedly smaller in the DST (figures 4.1 and 4.4) than in walking or running where knee ROM can reach 50° and 80° respectively (Murray, 1967; Mann and Hagy, 1980; Milliron and Cavanagh, 1990). This implied that in the DST, the leg swung forward in a rather straight position, because the landing ski can glide on the snow. In contrast to the DST, in walking and running the lower limb is brought forward in a flexed position to avoid the foot to trip on the ground with and reduce the lower limb moment of inertia (Perry, 1992; Novacheck, 1998).

In the DST, the leg was brought forward with open knee angle, the weight of the ski increasing the inertia of the lower limb. The large hip angular velocity peak during the swing phase (figure 4.3, HVelF1) and the stopping of the motion leg within the beginning of the stance phase (figure 4.3) supported the idea, previously developed by Gagnon, (1979) and Norman et al., (1985) that the swinging leg may be used for generating additional mechanical energy to the whole body. This has been further strengthened with the observation that the best skiers used the pendulum like movement of the swinging leg in a more efficient way for transferring kinetic energy to the whole body (Norman et al., 1985).

4.1.5.1.2 Stance phase

In accordance with studies on walking and running (Murray, 1967; Mann and Hagy, 1980; Novacheck, 1998), the stance phase has been described as the period the foot was in contact with the ground, involving the leg propulsion phase. In DST, the hip and knee ROM during the stance phase were larger than in walking and running at similar speed (i.e. 3.8 m/s) (Murray, 1967; Mann and Hagy, 1980; Milliron and Cavanagh, 1990; Biewener et al., 2004) (figure 4.2). The ankle ROM was reported to be similar between skier and runner (Milliron and Cavanagh, 1990; Biewener et al., 2004). These results may suppose that the DST exhibited different leg propulsion mechanisms.

The comparison of the magnitude of angular velocity peaks for the hip, knee and ankle confirmed this hypothesis showing that compared to similar speed running (Milliron and

Cavanagh, 1990), our results for the knee and ankle peaks of velocity flexion were dramatically smaller (figure 4.3). In running, flexion of the hip, knee and ankle resulted from the braking phase of the body at foot landing. This phase occurs over a short period of time (i.e. 20 ms), therefore generating large joint flexion velocity. In the DST, the flexion phase of the joints is not resulting from a braking phase but it is more a strategy to produce forces on the ground (i.e. in a similar manner to the countermovement jump). The DST propulsion mechanism required an active flexion / extension motion of the lower limb to 1) produce enough forces to obtain an efficient grip between the ski and the snow and 2) generate horizontal forces to move the body forward.

Physiologically, the flexion / extension pattern of the lower limb joints has been reported as a mechanism to potentiate the forces generated by the muscles (Komi and Bosco, 1978; Bosco et al., 1982, 1987). Our results supposed that such mechanisms would be used to improve skiing performance. This is in accordance with Komi and Norman (1987) whose observations supposed that in DST a stretch-shortening cycle (SSC) such as in running would occur for enhancing the muscle force production. However, regarding the delay between the joint flexion and the extension phase (approximately 260 ms), the SSC involved in DST is more comparable to vertical jumping movement (Bobbert and Van Ingen Schenau, 1988) than running (Komi, 2000).

As in many other sporting activities, the joint coordination strategy used for propelling the body (i.e. vertical jumping, running) showed an organisation of the segments flexion and extension phases into a proximo-distal activation of the joints. This common joint sequencing developed from mechanical and physiological constraints. Kreighbaum and Barthels (1981) reported that the proximal segments produced a downwards forces on distal segments that delayed their extension phase. Bobbert and Ingen Schenau (1988) completed this picture by adding the roles of biarticular muscles in the proximo-distal sequencing of the joints. Mechanically, this coordination strategy gradually changes the direction of the reaction force (Van Ingen Schenau, 1989). Kinetic studies in running (Miller, 1990) and the DST (Komi, 1985) showed a progressive increase of the horizontal component of the reaction force during the propulsion phase.

The comparison of the proximo-distal organisation of the lower limb segments in DST with previous studies on jumping movement (Bobbert and Van Ingen Schenau, 1988; Van Ingen Schenau, 1989) showed strong differences.

In vertical jumping, the extension of the hip joint begins at approximately 100 ms before the knee extension and 200 ms before the ankle plantar-flexion (Van Ingen Schenau, 1989). In the DST, the proximo-distal activation of the joints showed that the knee and the ankle were temporally coupled. This difference in the coordination strategy may suppose the influence of the material (i.e ski) and of the environment (i.e. snow). In ice skating, Van Ingen Schenau et al., (1985) reported that the leg propulsion during the forward glide did not allow any ankle plantar flexion to prevent the point of the skate scratching through the ice (Van Ingen Schenau et al., 1985). The modification of the design of the skate (i.e klapskate) allowed a complete proximo-distal sequencing of the joints to improve performance (Van Ingen Schenau et al., 1996). In DST, it can be argued that the temporal constraint of the grip between the ski and the snow (i.e. less than 40 ms) and the resulting gliding phase influenced the joints activation sequencing for the production of forces. This may result in a coordination strategy with a temporal coupling of the activation of the knee and ankle joints. In addition the coexistence of extension peaks of the knee and the ankle reflected the properties of the bi-articular gastrocnemius muscle (i.e. knee extensor and ankle plantar-flexor) (Van Ingen Schenau, 1989). The important activation of the gastrocnemius muscle has been reported in the DST (Komi, 1987; Komi and Norman, 1987).

4.1.5.2 Upper limb

The literature review highlighted that poles play a role in the generation of propulsive forces. Shoulder and elbow angular kinematics were investigated in order to determine the arm propulsion mechanism involved in the DST.

Our results showed larger shoulder and elbow ROM were observed in the arm cycle when compared to walking and running (Craik and Oatis, 1995; Hinrichs, 1990). An initial flexion phase in the elbow was observed prior to an extension phase occurring after the pole plant. Such observations were in agreement with previous work from Komi and Norman (1987). The shoulder angular velocity profile showed a peak of extension, which was concomitant with the elbow peak of flexion. This result would signify that the pole was brought close to the trunk, in order to reduce the torque about the shoulder and start the production of pole force. As proposed by Komi and Norman (1987) this mechanism may generate a SSC in the Triceps Brachii muscle, enhancing the arm propulsion force. Interestingly, unlike kinematic studies of upper-limb throwing

(Jöris et al., 1985; Alexander, 1991b; Temprado et al., 1997), the joints of the propulsion arm were not characterised by a proximo-distal organisation. Instead, the extension of the shoulder and the elbow seemed to be co-activated for generating sufficient propulsion force. This observation would seem to be logical since in throwing movement the objective is to generate high velocity for the distal segment, whereas in the DST, the objective of the skier was to generate larger pole force.

To conclude, this kinematic analysis of the DST aimed to describe the specific movement patterns required for skiing with a reference to walking and running. The differences in the joint angular patterns in the DST (compared to walking and running) reflected the particularities of the locomotion and to some extend that of the environment. During the swing phase, the gliding phase allowed the skier to emphasis the amplitude of the leg swing in order to generate further forward displacement. The utilisation of skis resulted in a specific segmental organisation of the limb segments for propelling the body that was different from that of walking, running or jumping. The arm propulsion was a co-participation of the shoulder and elbow joints for the generation a force.

In the scope of answering the research question, Study 1 provided a first body of data that described the joint movement used in the DST. Although this description allowed to better understanding the propulsion mechanisms used in the DST, study 1 did not provide a clear picture of how those mechanisms were generating the displacement of the body along the ground. Therefore, further analyses are required to relate the joint movement strategies with some indicators of the causes of movement.
Study 2 will analyse the fluctuations of the mechanical energies of the body centre of mass in the DST locomotion.

4.2 Study two: General mechanics of the DST

4.2.1 Rationale

"If we were to choose which biomechanical variable contains the most information, we would be forced to look at a variable that relates to the energetics. Without that knowledge, we would know nothing about the energy flows that cause the movement we are observing: and no movement would take place without those flows... Without them, we could have made erroneous or incomplete assessments that would not have been detected by EMG or moment-of-force analyses alone. Also valid mechanical work calculations are essential to any efficiency assessments that are made in sports and work-related tasks" (Winter, 1990).

This quote of Winter D.A. emphasises the importance of investigating the cause of the movement for having a deeper understanding of any sport or locomotion. Commonly in walking or running, the calculation of the energetics developed from the measurement of forces that generated the movement (Cavagna et al., 1964; Cavagna and Kaneko, 1977; Willems et al., 1995). In DST, kinetic investigations are much more difficult and hazardous, forcing the analysis of the locomotion to be based on the only kinematics. Although kinematic data are expressing the results of the movement, it can be used to estimate the energetics of the activity as reported in chapter 3 (section, 3.3.5).

The literature review and study 1 analysed the kinematic of the DST showing particular motor patterns resulting from the specificities of the environment. However, a lack of data exists with regard to the way the DST movement is produced. This study therefore aimed to use mechanical paradigms to better understanding and characterising the DST locomotion.

4.2.2 Introduction

The DST can be characterised as an additional human terrestrial locomotion since it showed stable locomotor patterns (pilot study and study 1). Unlike walking or running, the overall mechanisms for progressing on the ground have yet to be understood. Whereas kinetic studies were mostly descriptive (Komi, 1985, 1987; Pierce et al., 1987), most mechanical studies focused on comparing skiers of different performance level and calculating the exchange of energy within and between segments (Norman and Komi, 1987; Norman et al., 1989). Those studies reported that expert skiers favoured the pendulum-like movement of the swinging limbs. Only Minetti et al. (2001a) provided some overall mechanical insights on various technique of cross-country skiing such as skating, double poling and uphill DST. In this study they calculated the external (W_{ext}), internal (W_{int}) and total mechanical (W_{tot}) work of a 3.3 m/s DST over a 15% slope. A quantification of the ability of the body centre of mass to behave like a pendulum (i.e. energy recovery, Cavagna et al., 1976) has been calculated from the external work. Minetti et al. (2001a) observed a small apparent energy recovery value (10%) in uphill DST, and emphasised the similarities with running. The terrain condition and the restricted previous analysis relative to the DST justify the need for further mechanical investigations.

Overall mechanical descriptions of human and animal locomotion have exhibited three different paradigms for saving mechanical energy. Firstly during bipedal and quadrupedal walking, the body centre of mass (BCM) exhibited an exchange of kinetic and potential energy as in a pendulum (Cavagna et al., 1964, Alexander, 1992b). Secondly, during running and trotting, the body centre of mass showed a storage and release of energy in the elastic component of the tendon-muscle system and has been modelled as a bouncing ball or a child on a pogo stick (Alexander, 1992a). Third, both energy saving mechanisms are simultaneously operating such as in skipping and galloping locomotions (Minetti, 1998; Minetti et al., 1999). Therefore, the biomechanical literature on human and animal locomotion constitutes a strong basis for comparison with the DST locomotion.

The DST represents an original locomotion, because of the gliding phase, and may produce some additional knowledge on human terrestrial locomotion. In addition, mechanical analysis of the skiing locomotion may provide some useful information for coaches in order to refine or complete their training program.

A first purpose of this study was to measure the mechanical energy and work of flat DST and to characterise the locomotion with reference to other human locomotion, namely walking, running and skipping. The energy flows, the external work and internal work of flat DST were analysed at training speed. The study also aimed to detail the involvement of the different joints in the production of forward movement. Results from the mechanics and the kinematics of the DST were analysed together.

4.2.3 Methods

The subjects, equipment, protocol and data treatment were displayed in chapter 3. In this second study, the mechanical analysis of the conditions 1 (DST_n) was realised as reported in chapter 3 (section 3.3.5.3).

4.2.3.1 Data analysis

4.2.3.1.1 Cycle and mechanical analysis

Cycle velocity, cycle frequency and cycle length were calculated as in chapter 3 (section 3.3.5.1).

From the pseudo-3D trajectories of the body centre of mass, the time courses of the potential (E_P), horizontal (E_{KX}) and total energy (E_{TOT}) were calculated as reported in chapter 3 (section 3.3.5.3).

The external work (Wext), the internal work (Wint), and total work (Wtot) were calculated from the mechanical energies change of the body centre of mass (BCM) and of the segments centre of mass, as reported in chapter 3 (section 3.3.5.3). The internal work partitioning for each limb was calculated as the proportion of internal work done by each limb over the total internal work.

The energy recovery parameter (i.e. quantification of the ability to save mechanical energy by using a pendulum- like movement; Cavagna et al., 1976) was calculated as reported in chapter 3 (section 3.3.5.3).

4.2.3.1.2 Estimation of the effect of the snow friction and air drag forces on the E_{KX}

In the DST, the environment represents an important component leading to a modification of speed. To account for the impact of snow friction and air drag on the skier's velocity, an estimation of the environmental forces was calculated in accordance with previous work on the DST (Frederick, 1992; Smith, 2003). The details of the calculation are displayed in the equations 4.1 and 4.2.

- **<u>Snow friction</u>**

Equation 4.1: $\boxed{F_f = F_N \times \mu}$

where F_f is the snow friction force, F_N is the average ground reaction forces and μ the coefficient of friction.

According to Newton's second law, stating that the acceleration an object experiences will be directly proportional to the force applied (i.e. $F = m \times a$), Equation 1 can be rewritten:

Equation 4.1: $F_f = F_N \times \mu$

$$\Updownarrow \text{ With } F_N = m \times g$$

$$m \times a_f = m \times g \times \mu$$

$$\Updownarrow$$

$$a_f = g \times \mu$$

As g equalled 9.81 m/s^2 and μ is assumed to be 0.05, the deceleration generated by the snow friction (F_f) was $a_f = -0.49\, m/s^2$. The coefficient of friction of 0.05 was chosen in accordance with Frederick, (1992), Lind and Sanders (1996) and Smith (2003). Frederick (1992) reported that typical values of μ are less than 0.05 for most skis waxed for gliding on snow. Since μ has not been measured on the day of the experiment it may have been larger or smaller, increasing or reducing the snow friction force. As a result, this calculation should be taken as an overall estimation of the impact of snow on the skier velocity.

- **Air Drag**

Equation 4.2: $\boxed{F_D = \frac{1}{2}(\rho \times A \times C_D \times V^2)}$

Where F_D is the drag force, ρ is the mass density of air, A is the area facing the air flow, C_D is the coefficient of drag and V is the relative velocity.

Using Newton's second law, equation 4.2 can be rearranged:

Equation 4.2: $F_D = \frac{1}{2}(\rho \times A \times C_D \times V^2)$

$$\Updownarrow$$

$$a_D = \frac{(\rho \times A \times C_D \times V^2)}{2m}$$

With ρ, A and C_D respectively 1.25 kg·m^{-3}, 0.55 m^2, 0.9 (data taken from Frederick, 1992), $V = 5$ m/s and m=71 kg (i.e. the average mass of the subjects) the deceleration generated by the air drag was calculated to be $a_D = -0.11\,m/s^2$. As for the snow friction, ρ, A and C_D were not measured on the day of the experiment. Although they cannot be considered as true values, they represented an estimation of the effect of the air drag on the skier.

- **Estimation of the loss of cycle velocity from air and snow friction**

To account for the effect of snow friction and air drag on the average cycle velocity of the skier, the sum a_f and a_D was multiplied by the average cycle duration (CD) reported in study 1 (with CD = 1.49 s). Consequently the effect of snow and air friction on the cycle velocity was calculated to be $V = -0.89\ m/s$

Therefore without snow and air friction the cycle velocity would have been 0.89 m/s larger than the observed average cycle velocity of 4.04 m/s (skiing condition 1).

The impact of the frictional forces on the external work of the body centre of mass was estimated by calculating the change of kinetic energy (E_{KX}) between the estimated cycle velocity with ($v_b = 4.93\,m/s$) and the cycle velocity measured ($v_a = 4.04\,m/s$) using the formula: $\boxed{E_{KX} = \frac{1}{2}m(v_b{}^2 - v_a{}^2)}$

Where m =71 kg (i.e. the average mass of the subjects), v_a= 4.04 m/s and v_b= 4.93 m/s. The estimated kinetic energy loss caused by the snow and air friction over an entire cycle was approximately **283 J.**

The snow and air friction slowed down the skier significantly with an estimated decrease of E_{KX} of about 283 joules. Therefore skiers regularly need to produce propulsion forces to counteract the loss of E_{KX} resulting from the snow friction; otherwise, they will come to a stop.

4.2.3.1.3 Estimation of the efficiency of flat DST

The overall efficiency of the positive work done during locomotion gave an indication of the relative importance of the contractile versus the elastic behaviour of muscles

(Cavagna and Kaneko, 1977; Kaneko, 1990). The efficiency has been calculated as the total mechanical work, W_{TOT} (i.e. sum of internal and external mechanical work) divided by the energy expenditure (Margaria et al., 1963). In order to estimate the efficiency of flat DST, an energy expenditure value was taken from previous work on flat DST (Formenti et al., 2005) where it has been reported to be about 160 J/m, independent of speed.

4.2.3.2 Statistical analysis

Descriptive statistics (Mean ± Standard Deviation) were undertaken for each cycle and mechanical parameters from the 8 subjects.

4.2.4 Results

The average cycle and mechanical parameters values were reported in table 4.8. In the same graphs (figure 4.12, 4.14 and 4.15), curves pertaining to walking and running (Cavagna et al., 1976; Minetti et al., 1993), skipping (Minetti, 1998) and uphill DST (Minetti et al., 2001a) have been displayed for comparison.

Table 4.1: Mechanical variables (average ± SD) obtained during DST$_{fl}$. The illustrated mechanical work values do not include the one necessary to overcome snow friction and air drag.

Mechanical variables	
Cycle Velocity (m·s-1)	4.04 ± 0.38
Cycle frequency (Hz)	0.67 ± 004
Cycle Length (m)	6.04 ± 0.76
Total work (J/kg m)	1.34 ± 0.10
Internal work (J/kg m)	0.35 ± 0.06
External work (J/kg m)	0.99 ± 0.10
% Wint lower limb1	26.5 ± 3.1
% Wint lower limb2	25.9 ± 2.5
% Wint upper limb1	18.5 ± 2.4
% Wint upper limb2	16.4 ± 1.8
% Wint head trunk	11.6 ± 1.5
Energy recovery (%)	26.6 ± 4.9
Efficiency	0.59

4.2.5 Discussion

The purpose of this study was to investigate the mechanisms used in DST to progress along the ground through an analysis of the mechanical characteristics of the locomotion.

The characterisation of the DST was initiated by comparing the calculated values of internal work, external work, total work and energy recovery in walking, running, skipping and uphill DST. All the values are presented in figure 4.12.

4.2.5.1 Global mechanical indexes analysis

The mechanical measurements exhibited similarities and differences between DST_n and other gaits (figure 4.7). One can observe similar external work values between DST_n and running at a similar speed. This result may develop from rather similar vertical displacement of the Body Centre of Mass (BCM) in DST_n (study 1) and in running (Hinrichs, 1990).

In contrast, internal work was much lower in the DST compared to running or skipping. This observation resulted from the lower cycle frequency reported in the DST compared to similar speed running (Chapter 2, table 2.1). Over a fixed distance, the limbs were accelerated and decelerated less frequently with respect to BCM in the DST than in running (figure 4.7). The partitioning of the internal work in the body segment showed a good balance between the right and the left side. The trunk-head internal work represented approximately 11% of the total internal work, and showed a larger involvement of the segment in the DST compared to walking and running (Cavagna and Kaneko, 1977; Willems et al., 1995).

The percentage of recovery for the DST (i.e. an index of the pendulum-like interchange of potential energy and kinetic energy developed by Cavagna et al., 1976) showed intermediate values between flat running and skipping and walking (figure 4.7). This may suggest that opposite fluctuation of potential energy (E_P) and horizontal kinetic energy (E_{KX}) occurred within the DST cycle. Therefore in the DST the body centre of mass could act as a pendulum-like movement as observed in walking or skipping but in contrast to running (Cavagna et al., 1976). Nevertheless, the percentage of energy recovery observed in the DST was modest compared to the values of walking and skipping (reaching about 50 - 60 %).

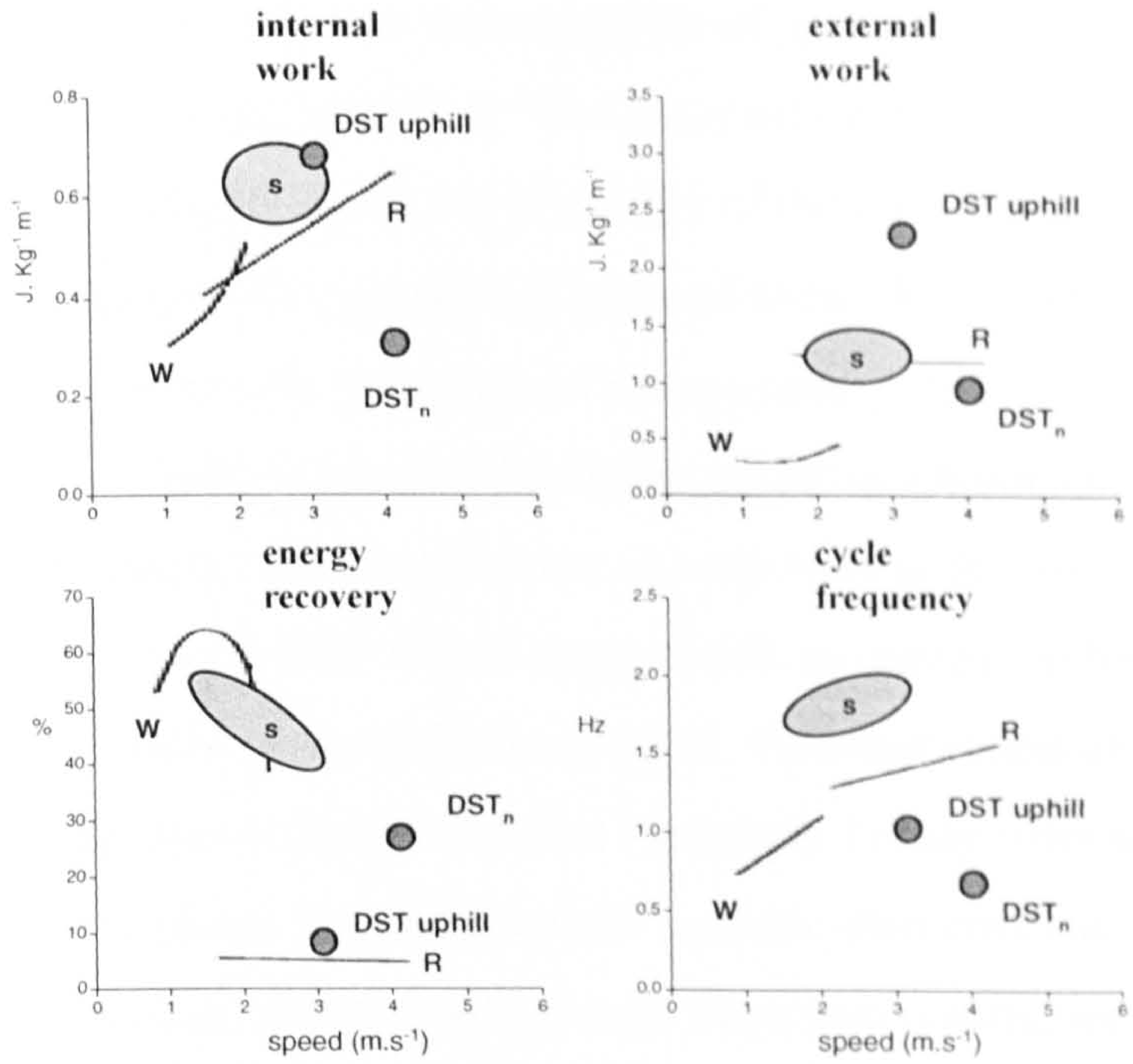


Figure 4.7: Summary of internal, external work, energy recovery and stride frequency measurements of diagonal stride technique (DST$_n$) compared with walking (W), running (R) and skipping (S) (Cavagna et al., 1976 and Minetti, 1998) and 15% uphill DST condition (Minetti et al., 2001a).

Previous work carried on the mechanics of uphill DST (+15% slope) showed an energy recovery value of 10 % (Minetti et al., 2001a). In walking and running, the slope reduced the speed fluctuations of the body centre of mass and proceeded to a monotonically ascending trajectory during each step (Minetti et al., 1993, 1994a; Minetti, 1995). This had a direct implication on the proportion of positive and negative work within the external work in the cycle. Whereas on flat terrain, the partitioning of the external work was 50% positive work (i.e. to accelerate the BCM) and 50% negative work (i.e. to decelerate the BCM) for both walking and running, uphill walking and running induced a change of this partitioning. For a slope of 15 %, the negative work is reduced to 3% in walking and to 25% in running (Minetti et al., 1994a). This state influenced the energy exchange (i.e. between the kinetic and potential energies) of the BCM during the cycle and also the metabolic cost of locomotion (Minetti et al., 1993, 1994a).

Therefore, the lower value of energy recovery in uphill DST in reference to flat DST was in accordance with the inherent characteristic of uphill legged locomotion where little space is given for energy exchange. The decrease of energy recovery between flat and uphill DST implies that the transfer of energy of the body centre of mass between E_P and E_{KX} was less marked. From a practical point of view, this observation showed that the skiing terrain will affect the technique of cross-country skiing.

The global mechanical indexes provided insights on the mechanics of the DST, leading to a first conceptualisation of the locomotion. As reported in the previous paragraph, the energy recovery value in the DST would suggest that an energy exchange between potential and kinetic energies occurred. In parallel, the observation of a flexion/extension sequence in the propulsion leg (study 1) may infer an exchange between a mechanical energy stored in muscle's elastic elements and both kinetic (E_{KX}) and potential (E_P) energies. Taking into account these two results, we may hypothesise that in the DST, like in skipping, these two energy-saving mechanisms would be active. To test this hypothesis, the time courses of energies (E_P, E_{KX} and E_T) in the DST were analysed and compared with the time-courses of energies of other gaits, such walking, running and skipping.

4.2.5.2 Mechanical energies analysis

Since the calculation of the mechanical work did not account for snow friction and air drag, it appeared essential to consider their theoretical impact on the kinetic energy of the BCM. Our results estimated that the snow and air friction decrease E_{KX} of the BCM at a rate of 280 J over the entire cycle (section 4.2.3.1.2). This loss of E_{KX} was illustrated by the blue dotted lines in figure 4.8. The decreasing gradient of the E_{KX} (purple curve, figure 4.8) during the swing phase was parallel to the blue doted lines (figure 4.8). This showed that the snow and air friction have an important impact on the kinetic energy change of the body centre of mass.

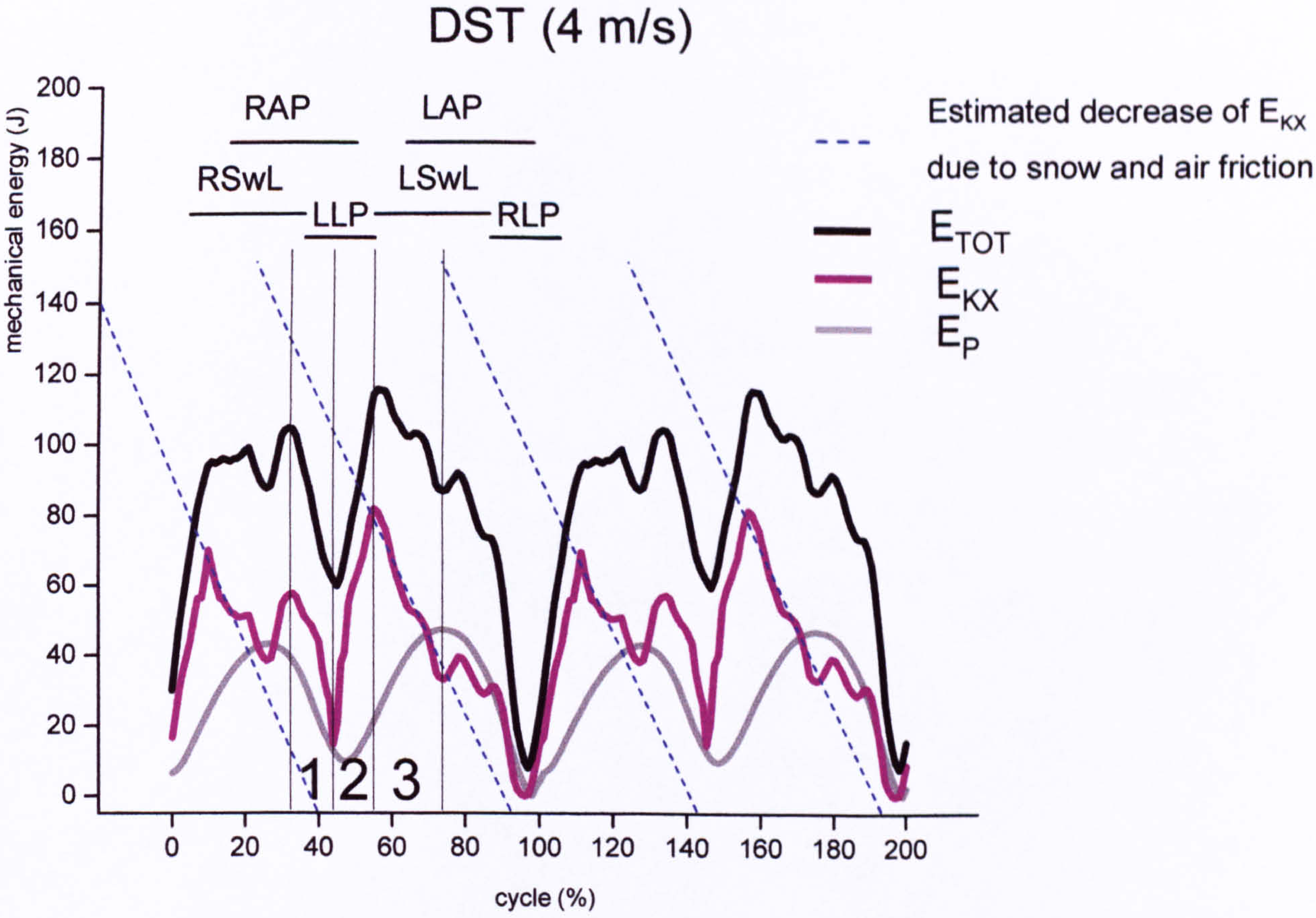


Figure 4.8: Average time-course of Potential (E_P), Kinetic (E_{KX}) and Total (E_{TOT}) energies for DST_n (n=8). The same stride has been duplicated for illustrative purposes.
LLP: Left leg propulsion; LSwL: left swing leg; RLP: Right leg propulsion; RSwL: Right swing leg; RAP: Right arm propulsion; LAP: Left arm propulsion. Blue lines represent the estimated decrease of E_{KX} over an entire cycle resulting from snow and air friction. 1, 2 and 3 represent the 3 periods taken from the patterns for analysis.

Figure 4.8 displayed average representative mechanical patterns of flat DST, from 8 subjects. The potential energy (E_P) curve showed two humps per cycle which can also be observed in walking, running (figure 4.9) and skipping (figure 4.10). Maximal values of E_P occurred during the second part of leg swing phases (RSwL, LSwL), whilst the minimal values occurred during the leg propulsion phases (LLP, RLP). The kinetic energy (E_{KX}) curve showed minimal and maximal values during the leg propulsion phase. During the swing phase, E_{KX} tended to decrease.

Compared to the three different mechanical paradigms reported in human locomotion (i.e. walking, running and skipping) (Minetti, 1998), mechanical patterns in the DST showed strong specificities. In contrast to walking and running, the potential and kinetic energy fluctuations did not present overall out of phase or in-phase relationships (figure 4.9). The shape of the mechanical energy-courses also differed from skipping. In this locomotion, the support phase featured an out of phase relationship between E_{KX} and E_P (figure 4.10).

The mechanical energy fluctuations in the DST exhibited characteristic periods during the cycle (figure 4.8, denoted 1, 2 and 3). These periods were analysed separately in order to document the overall mechanics of the DST locomotion. Periods 1 and 2 occurred during the leg propulsion phase and period 3 occurred during the leg swing phase.

Period 1 (figure 4.8) showed that both mechanical energies E_{KX} and E_P decreased in an in-phase relationship similar to running (Figure 4.9). In running, this has been reported as the expression of a storage of energy in the elastic components of the muscle-tendons structures. Mechanically, both E_{KX} and E_P have been reported to be stored as elastic energy (E_L) before being released in the system. Results from previous studies on the DST (study 1 and Norman and Komi, 1987) showed a flexion-extension sequence of the lower-limb joints and a stretch- shortening cycle in the muscles. We can confidently propose that in the DST during phase 1, E_{KX} and E_P have been transferred into E_L.

Our estimation of efficiency supported the idea of an energy transfer between E_L and E_{KX} and E_P. Our efficiency value of 0.59 was similar to values reported in running for a similar speed (Cavagna and Kaneko, 1977). Since the maximal efficiency of the transportation of chemical energy into positive mechanical energy by the muscles is about 0.25 - 0.30 (Woledge et al., 1985), greater values must indicate the intervention of muscle elastic elements (Cavagna and Kaneko, 1977) for increasing the positive work, free of cost. This suggested that the storage-release of elastic energy in the muscle constituted an important feature of the DST. However, in contrast to running where the transfer of energy between E_L and E_{KX}- E_P is total, in the DST, this transfer is thought to be incomplete. The snow friction and the stiffness of the ski may interact so E_{KX}- E_P could not be fully transformed into E_L.

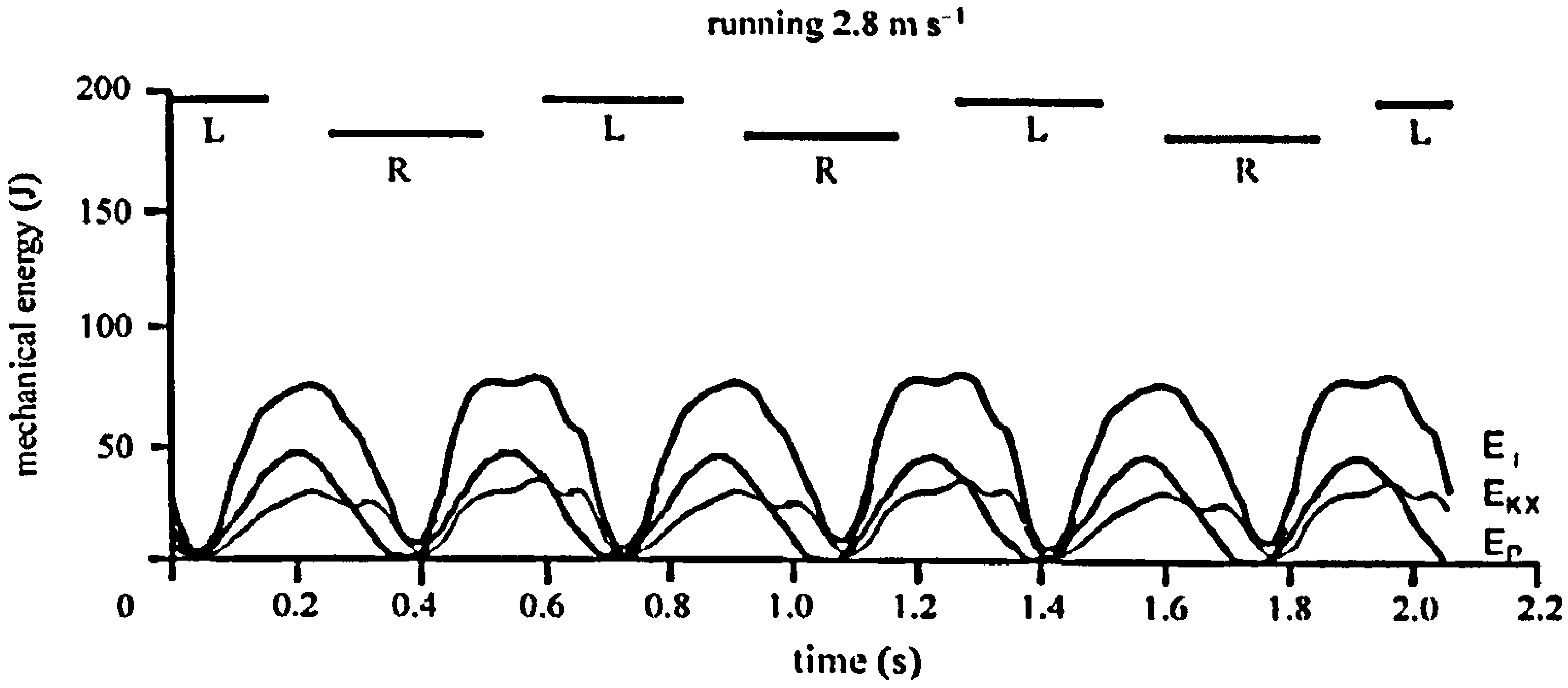


Figure 4.9: Time-course of Potential (E_P), horizontal (E_{KX}) and total energy (E_T) for running in a single subject (Adapted from Minetti, 1998).

In period 2 (figure 4.8), during the propulsion phase E_{KX} and E_P increased in an in-phase relationship. This observation was similar to those found in running (Cavagna et al., 1976; Cavagan and Kaneko, 1977). Mechanically, this may indicate that the accumulation of E_L in the elastic structures of the limbs (i.e. tendons and muscles) during the period 1 (figure 4.8) has been released into E_{KX} and E_P energies during the period 2. However, in contrast to running, the increase of E_{KX} did not coexist with a simultaneous increase of E_P (figure 4.9). E_P remained low over the duration of the augmentation of E_{KX} (figure 4.8). The maximum elevation of the BCM occurred later, in the swing phase (period 3).

The observation from periods 1 and 2 supported the idea that in the DST, mechanical energy exchanges occurred between the stored /released energy in the elastic structure of the muscles and E_P/E_{KX}.

During period 3, it can be observed that E_{KX} decreased whereas E_P increased (figure 4.13). This out of phase relationship between E_{KX} and E_P constituted a mechanical characteristic of walking gait that led the locomotion to be modelled as a pendulum (Cavagna et al., 1963; Cavagna and Margaria, 1966). In accordance with Cavagna et al. (1976), the energy fluctuations in period 3 may explain the rather high percentage of energy recovery (27%) observed in the DST which may suggest that the BCM acted as a pendulum during the swing phase.

However, by taking into account the snow and air friction effect on the BCM E_{KX}, a totally different image emerges. Indeed, the BCM decrease of E_{KX} was relatively similar to the estimated decrease of E_{KX} due to friction (blue line, figure 4.8). Therefore, it may be proposed that the decrease of E_{KX} observed in period 3 was not due to a transfer into E_P but to the snow as friction.

This contradicted the hypothesis previously stated in the text that a pendulum-like movement of the BCM was likely to occur in the DST as observed in walking.

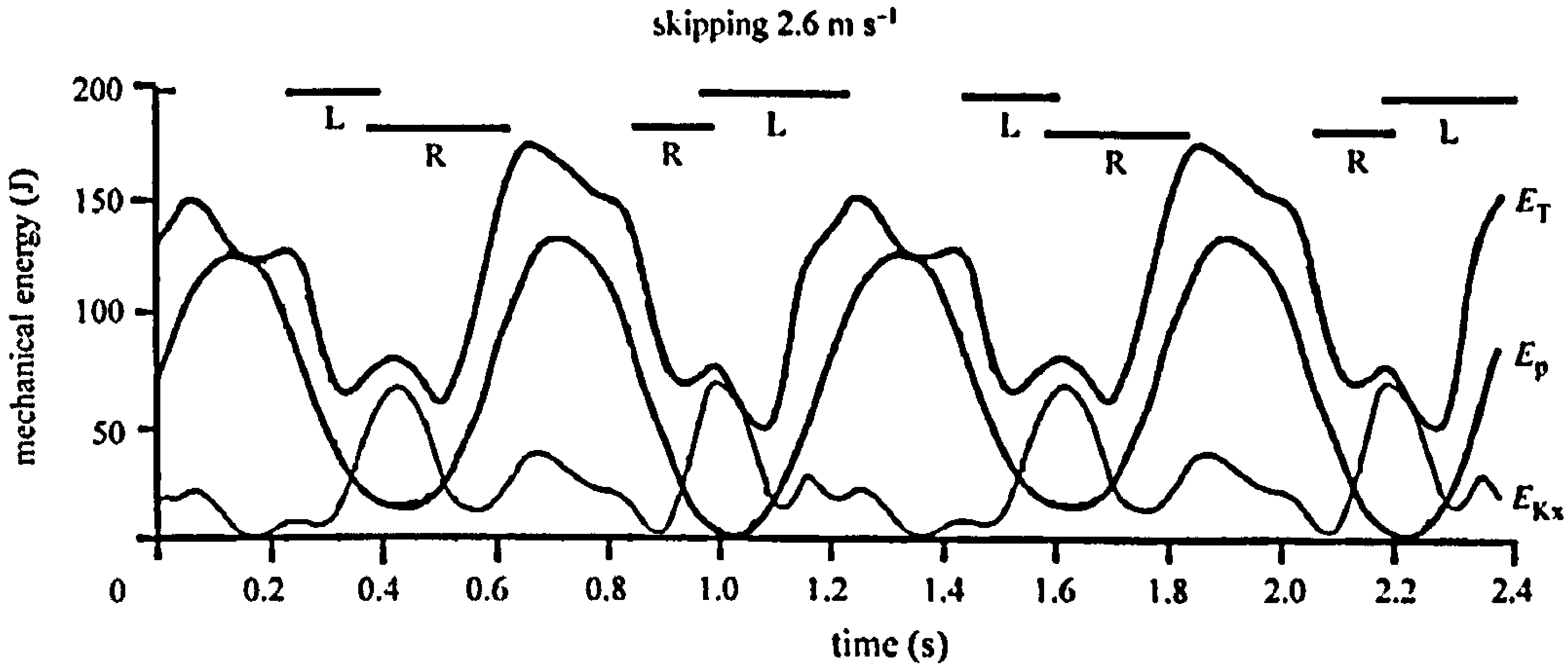


Figure 4.10: Time-course of Potential (E_P), horizontal (E_{KX}) and total energy (E_T) for skipping for a single subject (Adapted from Minetti, 1998).

The description of the 3 periods within the cycle showed that the elastic energy storage-release mechanism is the main energy-saving mechanisms used in the DST. This important result dismisses the possibility of any mechanical relationship with walking (i.e. potential-energy exchange). It also invalidated the hypothesis previously stated that, a simultaneous action of the 2 energy saving-mechanisms would occur in the DST as in skipping (Minetti, 1998) (figure 4.10).

Overall, the estimated efficiency (0.59) of the DST and the observation of the mechanical curves of the BCM supported the idea that the DST can be more closely related to running gait. The BCM energy exchanges in the DST may be represented as the one reported in running and hopping by Saibene and Minetti (2003) (figure 4.11).

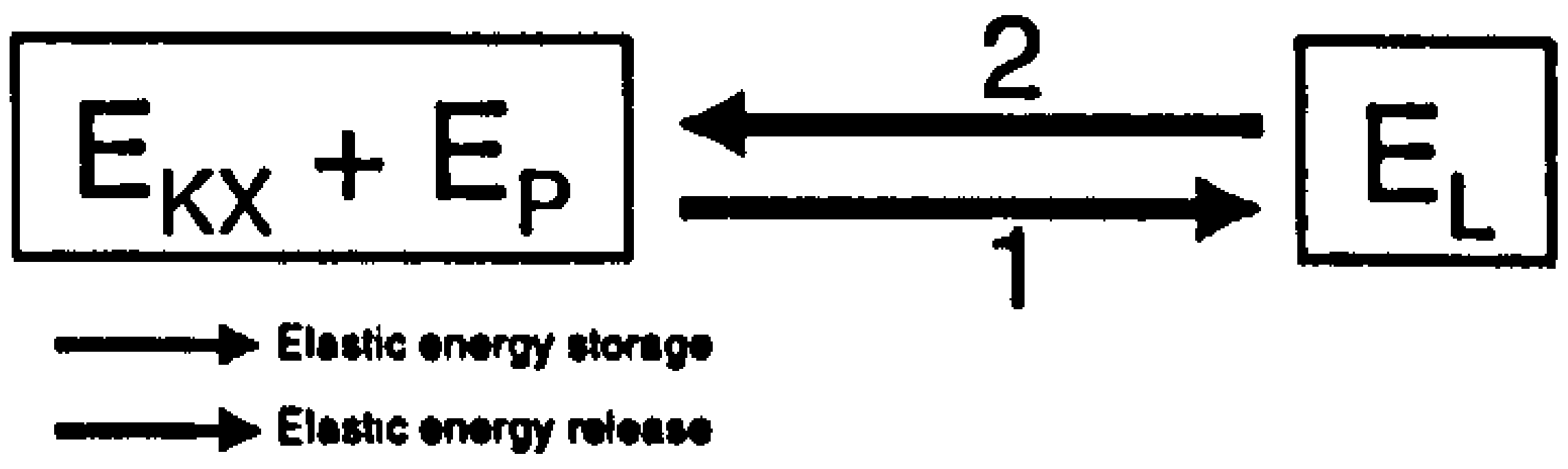


Figure 4.11: Mechanical energy flow assumed during the DST cycle; E_P represents the potential energy, E_{KX}, the horizontal kinetic energy and E_L, the elastic energy; 1, 2 correspond to phases depicted in the figure 4.8.

Although the same energy-saving mechanisms seemed to be used in running and DST, a close observation of time-course energy curves of both locomotions showed differences. In running the variation of E_{KX} is regular (figure 4.9). In the DST, the fluctuation of E_{KX} was observed to be inconsistent (i.e. rapid increase of E_{KX} and slow decrease of E_{KX}) (figure 4.8).

Those differences emerged from the gliding phase involved in the DST. In running the forward motion requires that some of the propulsion forces are generated to work against gravity. The flying phase supposed that the BCM is following a ballistic motion. In contrast, in the DST the body is gliding on the snow allowing a forward displacement with the body supported by the skis. The impact of the gliding phase can be concretely observed when comparing values of energy expenditure in running and DST. As displayed in figure 4.12, it cost 160 Joules to cover 1 meter in DST whereas in running it costs 200 Joules. An adaptation of recent work from Formenti et al. (2005) and Minetti (2004) provided a further view of the impact of gliding on human locomotion (figure 4.12). The speed-independent metabolic cost allows the estimation of maximum speed by dividing it by the available metabolic power, which depends on the journey duration. One can easily observe that at a similar speed, the DST skiers can cover nearly 10 times more distance than runners.

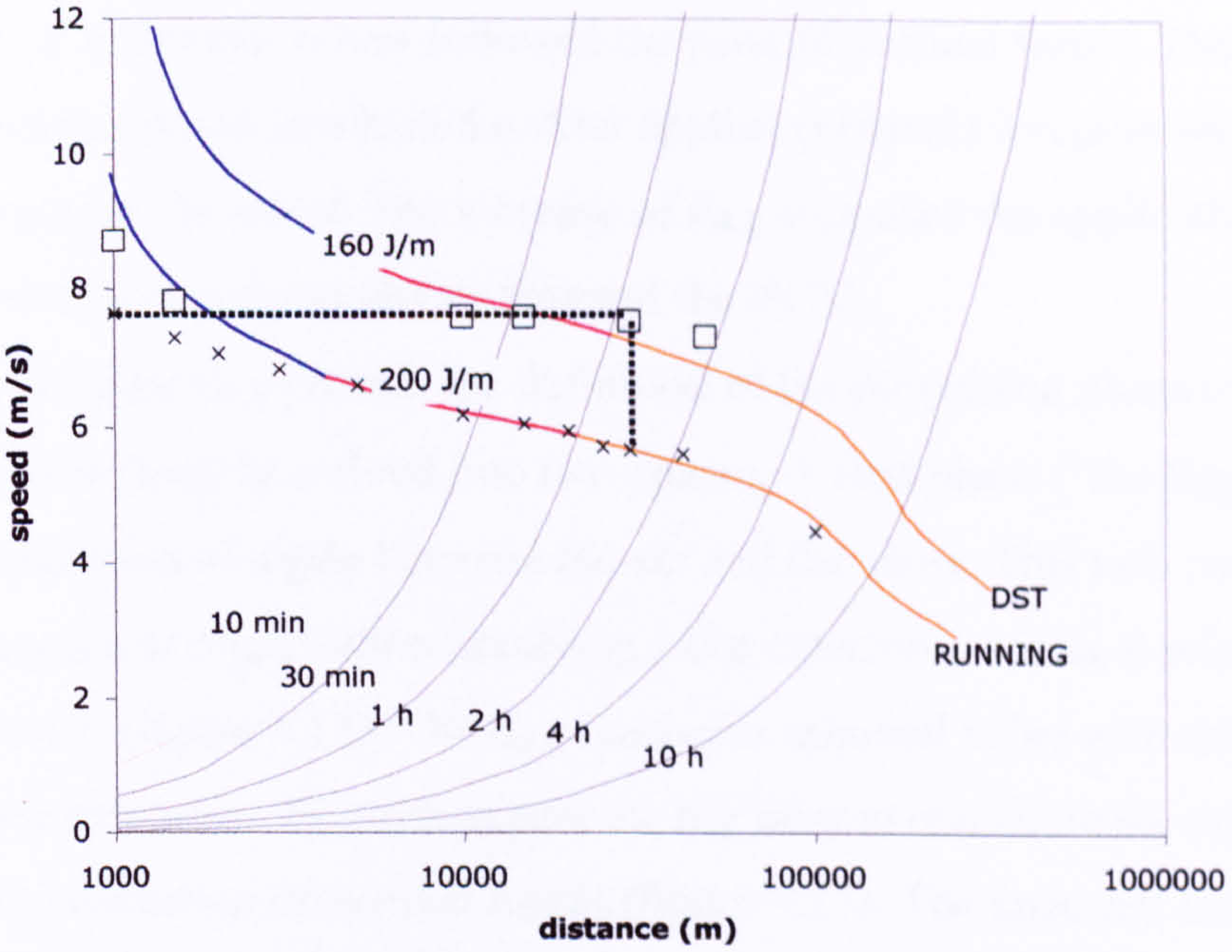


Figure 4.12: The 3 colours represent the maximum speed/distance relationship for metabolic cost, for the DST and running (Adaptation from Minetti (2004) and Formenti et al., 2005). They have been obtained by combining the relationships between time to exhaustion and available fraction of the metabolic power as suggested by Wilkie (1980), Saltin (1973) and Davies (1981) for different exercise duration ranges (blue: 40 s to 10 min, light orange: 10 min to 1h, and green: 1h to 24h, respectively). In the computational frame, 20.3 W/kg has been assumed as the maximum metabolic power available. The grey curves show iso-duration speed/distance pairs and the open square symbols represent recent records in cross-country skiing sprint events to endurance races. Crosses represent records in running from sprint events to endurance races.

4.2.5.3 Technique for progressing along the ground in the DST

The analysis of the mechanical energy curves of the BCM in the DST, provided a strong theoretical assessment of the energy saving mechanisms used in the locomotion. The analysis of the BCM kinetic energy also provided an overview of the speed generated during the DST cycle. In association with data reported in study 1 (i.e. a detailed description of the joint movements in the DST), the mechanical analysis may expand our understanding of the role played by the lower limb joints in the production of the skiing speed.

It can be observed that during the leg propulsion phases (LLP, RLP) there are periods when E_{KX} decreases (period 1, figure 4.8) and when E_{KX} increases (period 2, figure 4.8). As previously reported, during the propulsive phase of the DST the foot is constrained to a stop with respect to the ground, forcing the lower limb to extend backward relative to the body centre of mass (Hoffman and Clifford, 1992, Formenti et al., 2005). This foot immobilisation allows a grip between the ski and the snow that enables the generation of horizontal forces (Komi, 1985; Hoffman and Clifford, 1992). Komi (1985) reported that the generation of horizontal forces followed the peak of vertical forces. The decrease of E_{KX} may reflect the period in which the skier applies (vertical) forces in order to produce the necessary grip on the snow. The increase of E_{KX} supposed the application by the skier of horizontal forces to accelerate forward the BCM.

In accordance with the E_{KX} profile, the definition of the propulsion phase as proposed in the methods section may be refined into two phases. A first phase ("loading phase") allowed the generation of a grip between the ski and the snow. This task was achieved using joints segmental organisation involving a hip extension, a knee flexion and an ankle dorsi-flexion (figure 4.13). The E_{KX} reached a minimal value with the peak of hip angular velocity extension. One can expect the hip joint to constitute the main joint involved in the production of vertical forces (figure 4.13). The knee and ankle joint flexions may be adjusting the vertical component of the propulsion forces, and favouring a stretching of the muscles around the knee and the ankle joints. As the minimum value of E_{KX} was synchronised with the maximum flexion of knee angle, the loading phase may be defined from the moment the two feet are next to each other to the maximum knee angular flexion event (figure 4.13).

The second phase ("generation phase") involved in the propulsion phase, allows the generation of forward acceleration to the whole body. This phase involved mainly the rapid extension of knee and ankle joints. The "generation phase" can be defined from the maximum flexion of the knee joint to the lift of the middle part of the ski.

Having detailed the roles of the joints in the propulsion mechanisms, mechanical and kinematic data may also provide useful information relative to the importance of the swing phase. In accordance with previous work from Gagnon (1980) and Norman and Komi (1987) the swinging leg tended to contribute in the generation of velocity to the whole body. Figure 4.13 showed that the hip angular velocity was associated with an increase in the E_{KX} of the BCM. Although this relationship seemed logical, other sources may be generating these fluctuations. Pierce et al. (1987) and Komi (1985) showed that poles generated additional forces (estimated to be about 10-15 % of body weight) that may influence the BCM velocity. In addition, the swing phase fluctuations in E_{KX} may be originating from experimental noise.

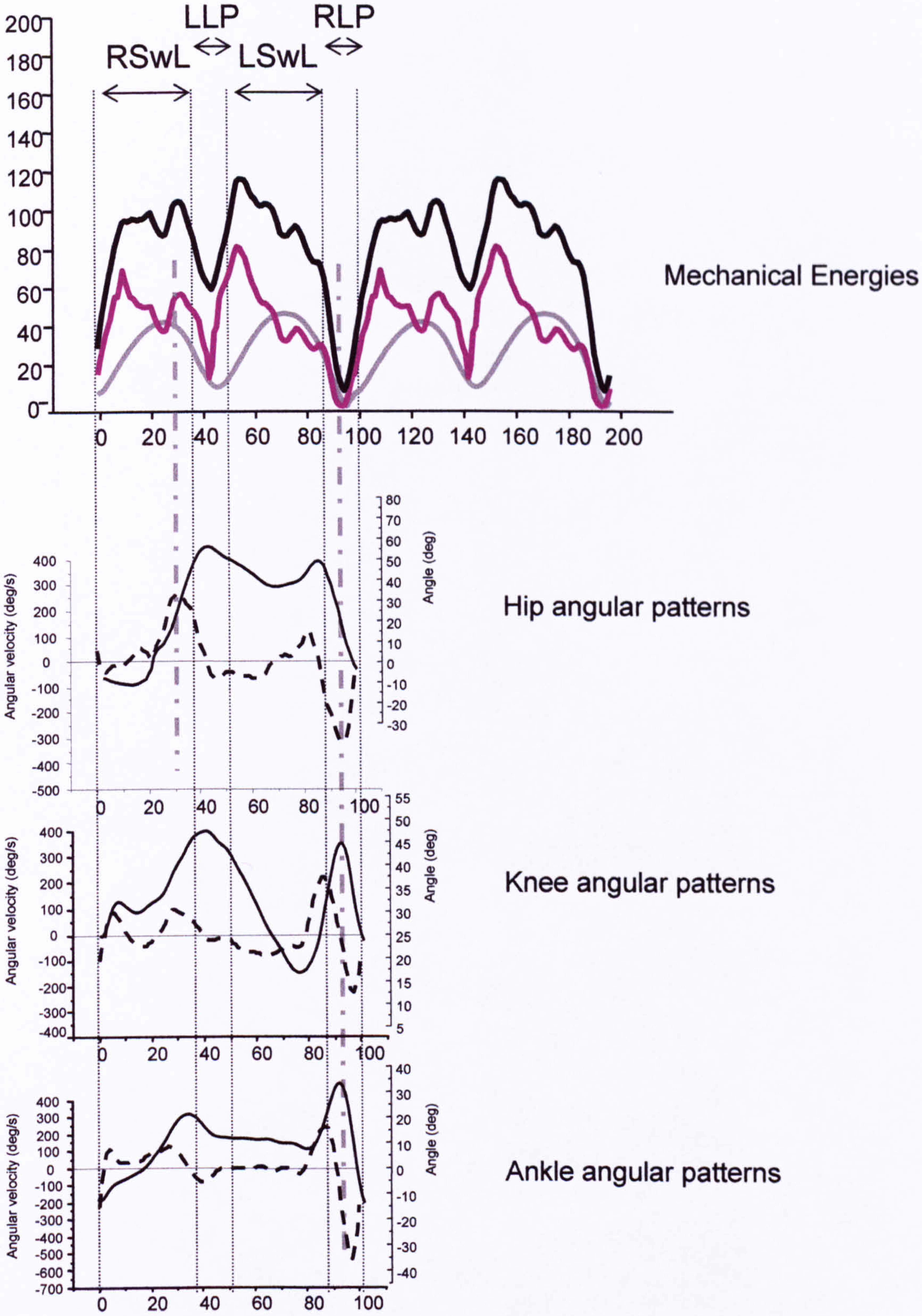


Figure 4.13: BCM mechanical energies patterns and hip, knee, ankle angular displacement and velocity. Line represents joint angular displacement patterns. Dashed line represents joint angular velocity patterns. Standard deviations were omitted for clarity.

To conclude, the determination of the general mechanics of the DST allowed a clear understanding of the energy flows that generated the movement. The value of internal work was lower in DST to that observed in similar speed running, benefiting from the lower cycle frequency. The energy recovery value was an intermediate value between running and walking and inferred the presence of inverted pendulum motion in the DST. However, the analysis of the mechanical energy curves (E_{KX}, E_P, E_{TOT}) dismissed this hypothesis showing that modifications in the E_P and E_{KX} BCM were independent of each other. The decrease of E_{KX} may result from the friction of the snow /air reducing the skier's speed. The mechanical energy curves showed that the energy-saving mechanism used in DST to progress along the ground was similar to the one observed in running. In DST, there is a large involvement of the elastic structures of the muscles for storage and release of elastic energy. Therefore, the DST locomotion was mechanically similar to running but involved a gliding phase. The glide enhanced the forward displacement resulting from the propulsion forces, hence increasing the cycle length and reducing the cycle frequency when compared to running.

The combination of kinematic and mechanical analyses provided good results for understanding the DST techniques used for progressing along the ground. The indispensable grip between the ski and the snow was achieved mainly from a hip extension. The generation of forward displacement was carried out using an effective extension of the knee and ankle joints during the propulsion phase. The swing phase and the pole propulsion were also observed to contribute to the forward displacement of the body.

This study 2 provided a strong basis of results for answering the research question. However, those analyses have been conducted on "complete" DST (i.e. involving upper body propulsion). Although the upper body propulsion forces have been reported rather low, the importance of the role of the poles in the locomotion is still to be investigated. This analysis will be completing our global understanding of the mechanisms used in DST to progress along the ground.

In Study 3, the kinematics of the DST was compared in condition with and without poles in order to describe the role of poles in DST.

4.3 Study three: Effects of poles on the kinematics of the DST

4.3.1 Rational

Today as during its early appearance, the DST is practised with poles (Lind and Sanders, 1996). One can easily experience that skiing without poles makes the displacement rather difficult. Therefore poles seem to be an important component of the locomotion. In the process of increasing our understanding of the DST locomotion, the roles of the upper body on the locomotion must be determined.

4.3.2 Introduction

In the DST, arms propel during 72 % of the cycle (i.e. study 1, figure 4.1) suggesting that the upper body is largely involved in the DST locomotion. In contrast, the pole reaction forces produced have been estimated to be rather small with 10-15 % of body weight (Komi, 1985; Pierce et al., 1987). Except for investigating force production, in the DST no study has investigated the effects of poles on the locomotion. In contrast, this analysis has been conducted in walking while practised with hiking poles (Jacobson et al., 1997; Schwameder et al., 1999; Willson et al., 2001). In these studies poles have been reported to have significant impact on the kinematics and energetics of the walking gait. In comparison to normal walking, poles reduced the load allocated to the hip and knee joints and increased the walker's lateral stability. They increased the walking speed because they generated additional force but increased the energy expenditure since larger muscular mass were solicited (Schwameder et al., 1999). In downhill walking, pole globally modified the posture of the walker for a more forward position (Schwameder et al., 1999). Therefore, the use of poles may be generating specific segmental organisation embedded in the DST technique. In addition to kinematic data, mechanical and coordination analyses may be of great use for characterising the roles of poles in DST. To study this, the selection of inter-limb (Whitall, 1989; Whitall and Caldwell, 1992) and intra-limb coordination (Hamill et al., 1999; Stergiou et al., 2001) analyses appeared useful since changes in the relationship between segments were related with modification of the stability of a system. This type of analyses may be appropriate for describing subtle changes in the coordination strategies following the loss of poles.

This study aimed 1) to understand the different roles played by the poles in the DST and 2) to further our understanding on their contribution for propelling the body along the ground.

Therefore, study 3 was to compare the cycle parameters, the joint kinematics, the mechanics, the inter-limb and intra-limb coordination between DST_n and diagonal stride technique without poles (DST_{wp}).

4.3.3 Methods

The subjects, the equipment, the protocol and the data treatment were as reported in the chapter 3 (section 3.3).

Study 3 analysed the kinematics of the DST locomotion with data from the condition 1 (i.e. DST normal speed, DST_n) and the condition 3 (i.e. DST normal speed without poles, DST_{wp}). One cycle for each subject was analysed for the 2 skiing conditions.

4.3.3.1 Data analysis

Cycle parameters (cycle velocity (CV), cycle length (CL), cycle frequency (CF), absolute and relative propulsion duration (PD and PD_r), absolute and relative swing duration (SwD and SwD_r) were calculated as described in the chapter 3 (section 3.3.5.1).

4.3.3.1.1 Joint angular displacement and velocity peaks

The range of motion (ROM) of the hip, knee and ankle during the leg stance and swing phases were calculated as reported in chapter 3 (section 3.3.5.2).

For each skiing condition, the leg joint angular displacement and angular velocity parameters reported in study 1 (figure 4.2 and 4.3) were investigated.

4.3.3.1.2 Mechanical analysis

From the 3D trajectories of the body centre of mass, the time courses of the potential (E_P), horizontal (E_{KX}) and total energy (E_{TOT}) were calculated as reported in chapter 3 (section 3.3.5.3). In addition, from the trajectories of the segmental centre of mass, the time courses of the kinetic energy (E_K) (i.e. translation plus rotational kinetic energy) were calculated as reported in chapter 3 (section 3.3.5.3).

The external work (Wext), the internal work (Wint), and total work (Wtot) were calculated from the mechanical energies change of the body centre of mass (BCM) and of the segments centre of mass, as reported in chapter 3 (section 3.3.5.3).

4.3.3.1.3 Inter-limb coordination

Inter limb coordination data treatment followed the methods proposed by Whitall and Caldwell (1992). To account for the temporal phasing between the upper and lower limbs, the event of the maximal flexion and extension of the upper arm and thigh segments (determined as the change in the sign of the angular velocity profiles) was expressed as a percentage of the cycle.

4.3.3.1.4 Intra-limb coordination

The calculation for the phasing relationship between the lower limb segments (thigh, knee and ankle) followed methods proposed by Hamill et al. (1999) and Stergiou et al. (2001a).

Phase plots (φ) were calculated for the thigh, leg and foot segments as the plot of the angle on the horizontal axis with its first derivative angular velocity axis. Phase plots were normalized in accordance with procedure described by Hamill et al. (1999) and Kurz and Stergiou (2002, 2004).

Relative phase represents the phasing relationships or coordination between the actions of the two interacting segments at every point during a specific period. Relative phase was calculated throughout the swing, support and propulsion phases by subtracting the phase angles of the corresponding segments: Ankle relative phase = φ Foot - φ leg and knee relative phase= φ leg - φ thigh.

The mean absolute relative phase (MARP) was calculated by averaging the absolute values of the ensemble curves points for the swing, support and propulsion phases (Stergiou et al., 2001a). Functionally, a low MARP value indicates a more in-phase relationship between the two segments' actions.

4.3.3.2 Statistical analysis

Mean (± StD) was calculated for each parameters studied. In order to determine the effect of the poles on the kinematics of the DST; the general spatial and temporal cycle parameters, joint range of motion, joint angular flexion and extension and joint angular velocity flexion and extension, inter-limb parameters and intra-limb parameters were compared between the DST_n and DST_{wp} using a sample related non-parametric test (Wilcoxon) with a significant level of $p<0.05$. The utilisation of this non-parametric test was justified in chapter 3 (section 3.3.6)

4.3.4 Results

4.3.4.1 Cycle parameters

Average cycle velocity (CV) in the DST without pole (DST_{wp}) was slightly lower than in DST_n (8% lower). Incidental to the diminution of CV, the cycle length (CL) was shorter in DST_{wp} compared to DST_n. The reduction of CL was produced by a 13% decrease of the swing length (SwL). In contrast the propulsion length (PL) remained constant. The temporal cycle parameters (i.e CF, PD, PDr, SwD and SwDr)) remained similar between the two skiing conditions (table 4.2).

Furthermore, one can observe that for each parameter, except CV, the standard deviation was larger in the condition without poles than in the condition with poles.

Table 4.2: Mean (± StD) of cycle parameters for DST_n and DST_{wp}: Cycle velocity (CV), cycle length (CL), cycle frequency (CF), absolute swing duration (SwD), absolute propulsion duration (PD), relative swing duration (SwDr) and relative propulsion duration (PDr).* significant differences between conditions DST_n and DST_{wp} with $p<0.05$. NS means no significant differences.

Cycle parameters	DST_n	DST_{wp}	
CV ($m \cdot s^{-1}$)	4.04 ± 0.34	3.69 ± 0.21	p=0.012*
Spatial parameters			
CL (m)	6.04 ± 0.57	5.60 ± 0.80	p=0.025*
SwL (m)	2.24 ± 0.37	1.96 ± 0.42	p=0.017*
PL (m)	0.84 ± 0.03	0.83 ± 0.06	NS
Temporal parameters			
CF (Hz)	0.67± 0.04	0.67 ± 0.08	NS
SwD (s)	0.56 ± 0.06	0.55 ± 0.12	NS
PD (s)	0.20 ± 0.02	0.21 ± 0.02	NS
SwDr (%)	37.11 ± 2.87	35.78 ± 3.06	NS
PDr (%)	13.25 ± 1.63	14.00 ± 2.11	NS

4.3.4.2 Joint angulations

4.3.4.2.1 Range of motion

The angular range of motion (ROM) of the hip, knee and ankle joints during the swing phase were similar between DST_n and DST_{wp}. In contrast, during the stance phase, the ROM of the hip, knee and ankle were increased significantly between DST_n and DST_{wp}

with data going from 62.9 ° ± 10.2 to 71.0° ± 10.6, from 30.4° ± 3.6 to 35.8° ± 3.6 and from 49.6° ± 6.3 to 56.4° ± 5.2 respectively (figure 4.14). The shoulder range of motion was significantly larger in the condition DST_n compared to condition DST_{wp} (142.3 ± 11.8 and 128.3 ± 6.8; $p = 0.012$).

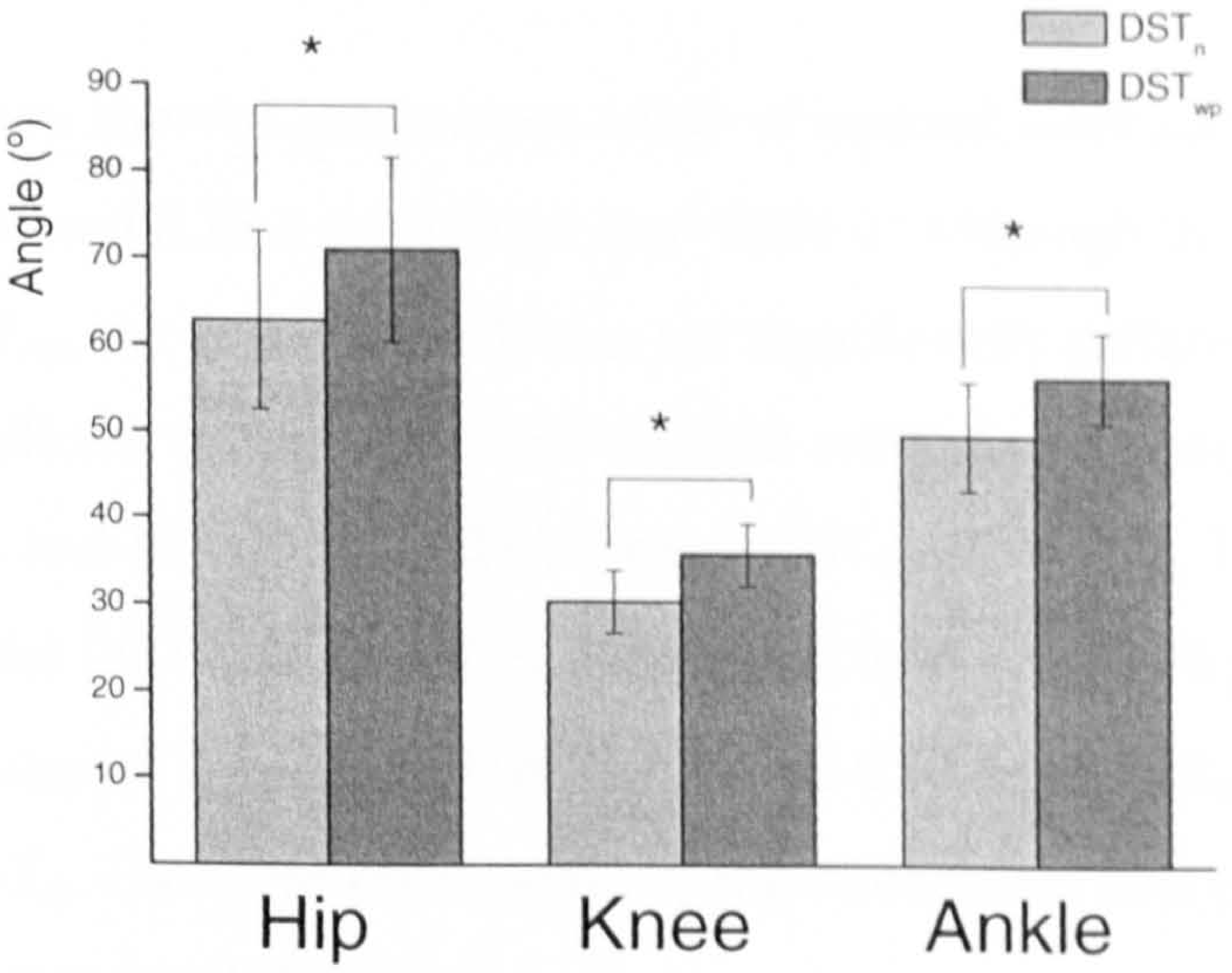


Figure 4.14: Range of motion reported for the hip, knee and ankle during the stance phase in DST_n and DST without poles (DST_{wp}). (*significant difference between DST_n and DST_{wp} with a level $p<0.05$)

4.3.4.2.2 Joints angular displacement and velocity peaks

Limbs extension and flexion have been compared between DST_n and DST_{wp}: DST_n presented smaller hip extension at the beginning of the swing phase (figure 4.2; HE1) than in DST_{wp}. In parallel, larger hip and knee flexion at the beginning of the stance phase (HF1 and KF1) have been observed in DST_{wp} compared to DST_n (table 4.3).

Table 4.3: Mean angular values (± StD) for the previously reported (figure 4.2) hip flexion (HF1), the hip extension (HE1) and the knee flexion (KF1) in condition DST_n and DST_{wp} (*significant difference between DST_n and DST_{wp} with a level $p<0.05$).

	DST_n	DST_{wp}	P value
HE1 (°)	12.1± 5.3	8.1 ± 6.2	p=0.012*
HF1(°)	59.8 ± 11.5	66.6 ± 10.2	p=0.012*
KF1(°)	46.7± 5.2	51.1 ± 4.4	p=0.036*

In contrast, no differences between DST_n and DST_{wp} were observed in the hip, knee and ankle joints angular velocity flexion and extension peaks (HVelF1, HVelF2, HVelE, KVelF, KVelE, AVelD and AVelP).

4.3.4.3 Mechanical analysis

The DST_{wp} condition showed larger mean value of internal work compared to DST_n (0.41 ± 0.06 J/kg/m and 0.35 ± 0.06 J/kg/m; p= 0.003). Although the skiing speed was smaller in the DST_{wp}, the external work was not significantly different to the DST_n. This resulted from significant differences in the vertical and forward components of the external work (W_v and W_f) of the BCM between DST_n and DST_{wp}. Larger values of W_v were observed in the DST_{wp} (0.41 ± 0.07 J/kg/m and 0.36 ± 0.05 J/kg/m; p= 0.007) whereas larger values of W_f (0.82 ± 0.08 J/kg/m and 0.90 ± 0.08 J/kg/m; p= 0.03) were reported in the DST_n. The close observation of the mechanical energy patterns of the BCM did show any major differences.

4.3.4.4 Inter-limb coordination

The effect of poles was investigated with measures of coordination between the upper and lower limbs. The analysis of the occurrence in the cycle of the four limbs maximal flexion and extension showed a strong side to side symmetry in DST_n (figure 4.15). Indeed no statistical differences were observed:

- Between the right arm maximal flexion (RAF; 4.0 % ± 3.5) and the left leg maximal flexion (LLF; 6.2 % ± 2.3)
- Between the right leg maximal extension (RLE; 8.4 % ± 3.2) and the left arm maximal extension (LAE; 7.6% ± 4.2).
- Between the right leg maximal flexion (RLF; 49.2 % ± 4.1) and the left arm maximal flexion (LAF; 51.6 % ± 2.8).
- Between the right leg maximal extension (RAE; 54.4 % ± 2.4) and the left arm maximal extension (LLE; 56.9% ± 2.3).

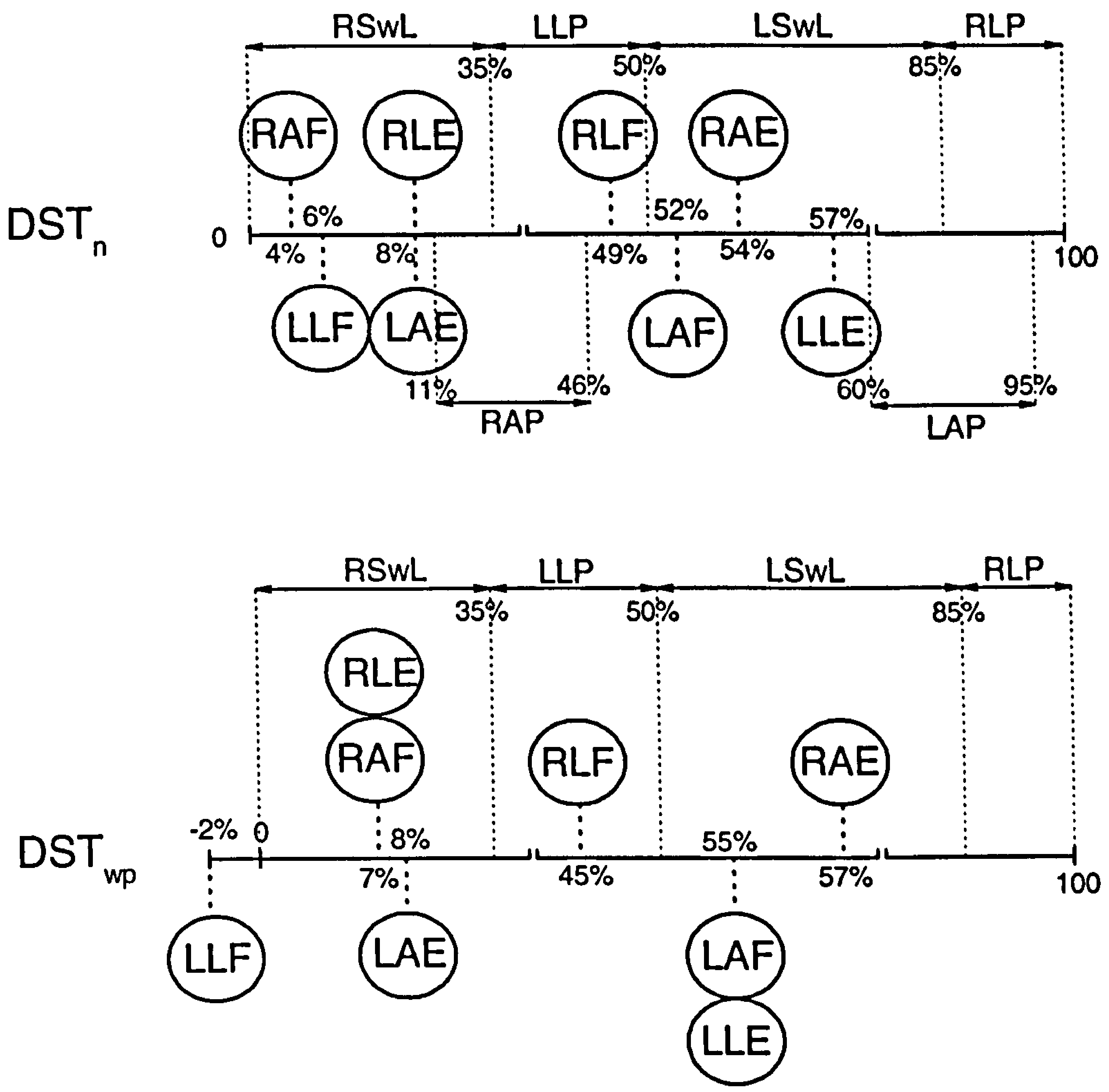


Figure 4.15: Occurrence of the right and left limbs maximum flexion and extension during DST$_n$and DST$_{wp}$ cycle. Data is expressed as a % of the cycle. Cycle was defined as in section 3.3.5.1.
RSwL: Right swing leg; RLP: Right leg propulsion; LSwL: Left swing leg; LLP: Left leg propulsion; RAP: Right arm propulsion; LAP: Left arm propulsion.
RLE: Right leg extension; RLF: Right leg Flexion; LLE: Left leg extension; LLF: Left leg flexion; RAE: Right arm extension; RAF: Right arm flexion; RAE: Left arm extension; LAF: Left arm flexion.

In DST$_{wp}$, the occurrence in the cycle of the maximum flexion and extension of the limbs was modified compared to DST$_n$ (figure 4.15). The maximum flexion of the arm occurred later in the cycle in DST$_{wp}$ condition (p= 0.025 for the right arm; p= 0.035 for the left arm). In contrast, the maximum flexion of the lower limb occurred earlier in the cycle (p=0.012 for the right leg; p=0.042 for the left leg).

4.3.4.5 Intra-limb coordination

The average absolute relative phase (MARP) was calculated as an indicator of the phasing relationship between the segments throughout the swing, support and propulsion phases. MARP for the knee and the ankle was calculated for each phases involved in the cycle: swing phase, support phase and propulsion phase. No significant differences were observed between DST_n and DST_{wp} in the swing phase and support phase. In contrast, the knee and ankle MARP values were larger in condition DST_{wp} during the propulsion phase (table 4.4).

Table 4.4: Average absolute relative phase (± StD) for the knee and ankle joint during the propulsion phase in DST_n and DST_{wp} (*significant difference between DST_n and DST_{wp} with a level $p<0.05$).

	DSTn	DSTwp	P value
Knee	15.13 ± 4.49	26.51 ± 8.96	p=0.024*
Ankle	31.86 ± 9.24	41.06 ± 8.08	p=0.016*

4.3.5 Discussion

The purpose of this study was to analyse the kinematic, mechanics and coordination differences between the DST in condition with poles (DST_n) and without poles (DST_{wp}) in order to define the roles of poles in the DST locomotion and their contribution in the forward displacement of the body.

As reported in studies 1 and 2, general cycle parameters and angular values observed were consistent with previous studies on the DST at similar speeds (Gagnon, 1981; Roy and Barbeau, 1991; Bilodeau et al., 1992; Nilsson et al., 2004). The hip, knee and ankle angular displacement values were also consistent with previous studies on the DST (Gagnon, 1980; Komi and Norman, 1987; Komi et al., 1982).

Although kinematic and mechanical differences existed between the DST_n and DST_{wp}, the general structure of the locomotion was not affected. Indeed the proportion of the phases in the cycle (i.e. SwDr and PDr) and the joint kinematic and mechanical energy patterns remained unchanged between the DST_n and DST_{wp}. These observations exhibited that the DST locomotion used robust motor patterns that were not disturbed by the loss of poles. The temporal invariant feature of the locomotion may simplify the control of movement by the motor-neural system (Nilsson et al., 2004). In both DST conditions, the coordination between the upper and lower limbs showed during the swing phase: 1) an ipsilateral hip flexion while the contralateral leg was extended and 2) the contralateral arm flexed. Interestingly this segmental organisation has been already observed in human walking while the subjects experienced a slip at heel strike (i.e. section 2.4, figure 2.26 (Marigold et al., 2003). In these studies it was observed that, with practise a "surfing strategy" appeared which consisted in delaying the landing of the contralateral unperturbed leg (Marigold et al., 2003). In the DST, this strategy is exploited to a maximum, delaying the forward movement of the leg, to allow a large gliding phase. The observation of similar segmental strategies in walking and in DST suggested that these strategies represented an efficient way of dealing with a gliding environment, and hence are dynamically stable.

The removal of poles affected the kinematics, mechanics, inter and intra segmental coordination of the DST locomotion. The cycle velocity was reduced by 7 % in comparison to the DST_n condition. This loss of speed between DST_n and DST_{wp} essentially resulted from a diminution of cycle length. Indeed the decrease of the cycle length was due to a diminution in the swing phase length. This resulted in an increase of the internal mechanical work for the condition without poles as more flexion / extension sequencing of the limbs occurred over a set distance. It can be proposed that the decrease of skiing speed would be consequent of the loss of upper body propulsion which occurs mainly during the swing phase (see Figure 3.9). However it may be the result of strategy adopted by the skiers to cope with the loss of stability given by the poles.

The loss of poles also influenced the kinematics and mechanics of the DST locomotion. The ROM of the hip, knee and ankle during the stance phase was larger in DST_{wp} compared to DST_n. These, resulted from a smaller hip extension at the start of the swing phase and larger hip, knee and ankle joint flexion towards the end the swing phase. Both results suggested that the kinematic changes constituted a means to maintain the stability / balance of the skier when losing the poles. The smaller hip extension may reduce the disturbance to the body balance that can be produced by the displacement of limb while gliding. In addition, the skier adopted a more flexed body position during the stance phase. In accordance with the values of vertical component of mechanical work data, it may be proposed that in DST_{wp} the skiers were lowering their body centre of mass in order to increase stability. The position of the body centre of mass and the centre of pressure have been reported as the two main variables regulating the body's balance (Winter, 1995; Burdet, 2003). Poles can hypothetically affect the position of the centre of pressure because from DST_n to DST_{wp} the skier shifted from a four to a two supports. In condition without poles, as the body weight is oscillating from one leg to another, the centre of pressure may translate from a position underneath one foot to a position underneath the other foot. In DST_n, one can expect that the pole support will restrain the displacement of the centre of pressure to an intermediately position between the pole stance of the contralateral foot. With poles the body centre of pressure might be less laterally displaced, so it adopt a more forward directed displacement. It may have for consequence to improve the balance of the skier.

With the loss of poles occurred a change of the inter-limb coordination. Indeed, the maximum thigh flexion was earlier in the cycle whereas the maximum arm flexion was delayed in the cycle. In accordance with previous observations, this inter-limb coordination facilitated the BCM to be lowered sooner during the cycle. Interestingly, this inter-limb phasing coordination observed in DST_{wp} was similar to that reported in running where thigh reversal preceded the arm reversal (Whitall and Caldwell, 1992). During DST_{wp} the skiers may use "classical" inter-limb coordination experienced in running. In DST_n, the delay of the arm flexion increased the propulsion path of the upper body, maximising the poles propulsion forces.

Whereas the poles seemed to be facilitating the balance of the skiers, the intra-limb coordination results showed that the poles may also be impacting on the lower limb coordination during the propulsion phase. A more out of phase relationships between the thigh and the shank and between the shank and the foot have been observed during the propulsion phase in the DST_{wp}. Previous studies have suggested that the changes in the relationship between the lower extremity segments (i.e. using continuous relative phase) reflected a change in the coordinative structure that may lead to injuries (Hamill et al., 1999) or instability (Stergiou et al., 2001a; 2001b). In the DST_{wp}, one may propose that the propulsion movement was more "uncoordinated", and may be less effective and dynamically unstable. The decrease of skiing speed between DST_n and DST_{wp} could be the result of a less efficient propulsion phase. By reducing the lateral displacement of the BCM, the poles help the skiers to produce a more coordinated and maybe more efficient propulsion mechanism. Expert skiers may be gaining in training without poles to improve the phasing relationship of the segment during propulsion. The collection of additional kinematic and kinetic data over uphill terrain in future studies would be useful to clarify the relationship between coordination and forces developed.

In conclusion, poles are considered to have two main functions in DST locomotion. They produced additional forces for sustaining the skiing speed whiles the skier is gliding and subjected to snow friction. They also increased the balance of the skier by providing additional supports. To compensate for the loss of poles, the skiers adopted a more flexed posture during the swing phase to increase balance.

Although poles were not influencing the general structure of the locomotion (i.e. temporal cycle parameters and joint angular profiles), they seemed to increase the gliding phase and may improve the segmental coordination strategy during the propulsion phase. With regard to the thesis research question, this study provides useful information to consider the poles as important implement for facilitating the execution of the DST technique and therefore the generation of speed.

As the skiers are capable of skiing at different speed, the analysis of the strategies used to increase speed in DST constitutes additional information that are crucial for characterising the biomechanical techniques used by humans for travelling on the snow. In study 4, the kinematic changes were analysed for fast and normal speed DST.

4.4 Study 4: Effects of speed on the kinematics of the DST

4.4.1 Rational

The human body is capable of skiing over a wide range of velocities. The DST can be practised from very slow speeds to speeds up to 9 $m \cdot s^{-1}$ (Bilodeau et al., 1996). The description of the strategies for increasing speed in the DST is of interest for the characterisation of the locomotion and to better understand the performance in skiing.

4.4.2 Introduction

Analyses of the kinematic modifications of gait with velocity change have been crucial in the description of functionally cyclic gaits (Rosenrot et al., 1980; Hay, 2002). They provided important knowledge into the understanding of the neural generation of locomotion and allowed for the comparison between gaits of the differing motor patterns (Nilsson et al., 1985).

The DST constitutes an additional form of human locomotion on snow that has been shown to have characteristic segmental patterns and co-ordination (Study 1). However, the kinematic adjustments of the skier to increased translational velocity have been poorly documented. Three studies analysed the changes in the general cycle parameters with velocity increase but reported contradictory results (Gagnon, 1981; Roy and Barbeau, 1991; Nilsson et al., 2004). Roy and Barbeau (1991) observed an increase of both cycle velocity and cycle length with velocity increase whereas Gagnon (1980) and Nilsson et al. (2004) reported only a change in cycle frequency for a similar velocity change. Only one study has investigated the modification of joint angular motion but only focused on leg recovery (Gagnon, 1980). Therefore, there is a need for further analysis of the DST kinematics in order to bring a more detailed description of the evolution of the general cycle parameters with velocity change. A further knowledge of whole body segmental adjustments with velocity increase will be produced. In addition, these data will constitute another step in the characterisation of the DST with comparison to human walking and running.

This study investigated 1) the general cycle parameters and 2) in the lower and upper limb angular displacement and velocity with velocity increase.

4.4.3 Methods

The subjects, equipment and set up, and data treatment were as reported in the chapter 3 (section 3.3).

4.4.3.1 Data Analysis

In this study, the data from condition 1 (i.e. normal speed, DST_n) and condition 2 (i.e. racing speed, DST_f) were analysed (chapter 3 section, 3.3.3). As in racing condition DST_f, the cycle lengths recorded were large; the recording of a full cycle was not possible. Hence, no mechanical analyses were performed. The analysis of the strategies for increasing speed in DST involved only kinematic parameters (cycle and angular).

4.4.3.1.1 Cycle parameters

The definition of the cycle, swing phase and propulsion phase were as reported in chapter 3 (section 3.3.5.1). The cycle length (CL) and cycle duration (CD) were calculated as the sum of the two half cycle length and durations.

Cycle velocity (CV), cycle frequency (CF), absolute propulsion (PD) and swing duration (SwD), relative propulsion and swing duration (PDr and SwDr), arm propulsion duration (PPD), propulsion and swing lengths and arm propulsion length have been calculated as reported in chapter 3 (section 3.3.5.1).

4.4.3.1.2 Angular parameters

The range of motion (ROM) of the shoulder and elbow during the arm propulsion and the ROM of the hip, knee and ankle during the leg propulsion and swing phases were calculated as reported in chapter 3 (section 3.3.5.2).

The trunk angle was investigated and defined as the angle between the line hip-shoulder and the vertical (figure 4.16).

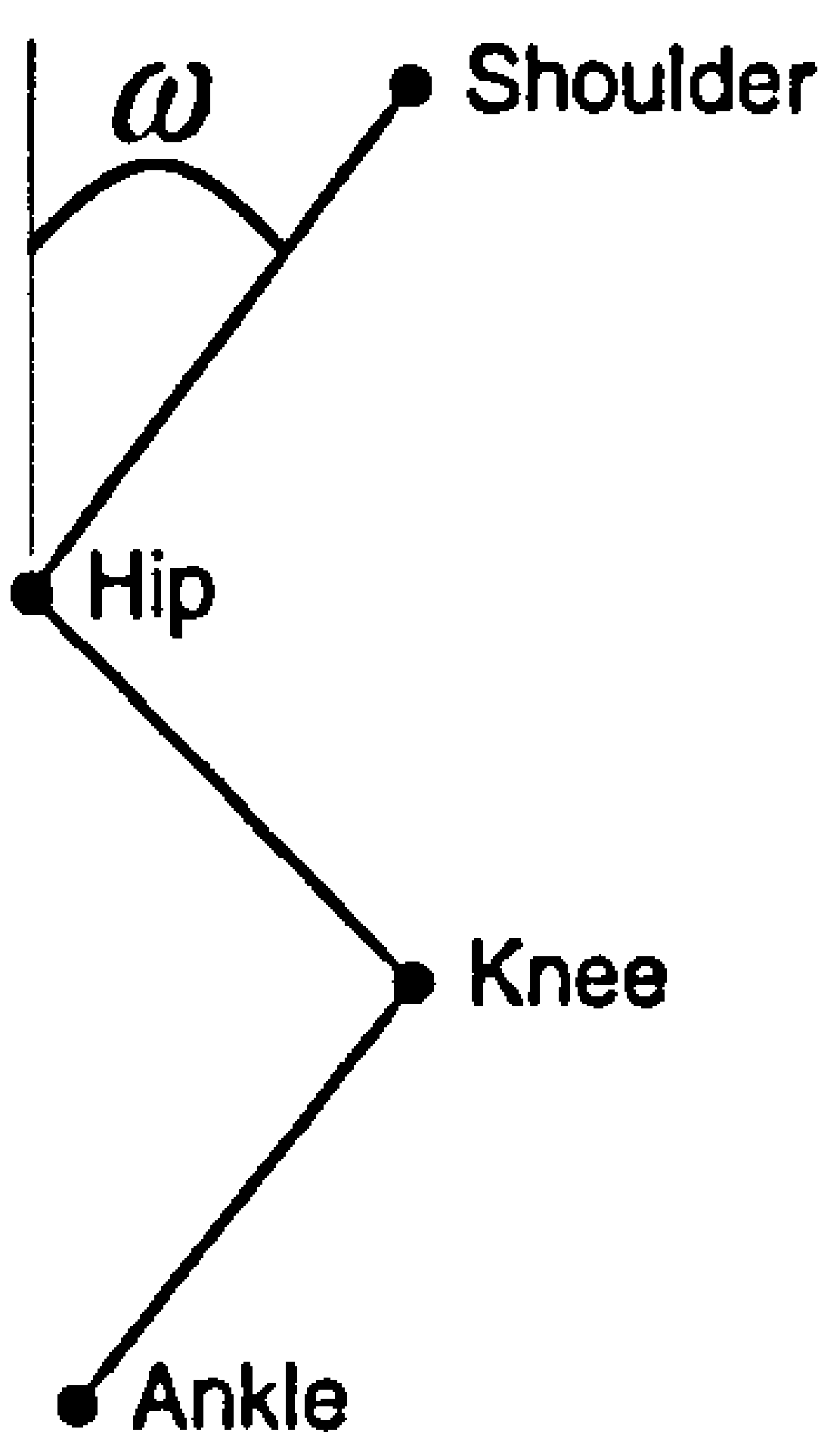


Figure 4.16: Schema defining the trunk angle (ω).

The ROM trunk from DST_n and DST_f was also calculated for the propulsion and swing phases, as the difference between the maximal and the minimal values observed in the phases.

All joints angular and angular velocities peaks reported in study 1 (figure 4.2, 4.3 and 4.6) have been investigated in this study for both skiing condition 1 and skiing condition 3.

4.4.3.2 Statistical analysis

Mean (± StD) was calculated for each parameter studied. In order to determine the change generated by the increase of speed on the kinematic of the DST; the general spatial and temporal cycle parameters, joints range of motion and joint angular velocity flexion and extension peaks were compared between DST_n and DST_f using a sample related non parametric test (Wilcoxon) with a significance level of $p<0.05$. The utilisation of a non parametric test was justified in chapter 3 (section 3.3.6)

4.4.4 Results

4.4.4.1 General cycle parameters

4.4.4.1.1 Absolute values

The cycle velocity increased by approx. 27 % between the two speed conditions DST_n and DST_f. This increase resulted from an 18% augmentation of the cycle frequency and a 10 % increase of the cycle length. Between DST_n and DST_f, PD, SwD, PPD demonstrated large decreases whereas PL, SwL and PPL increased in a more moderate manner (table 4.5).

Table 4.5: Mean (± StD) absolute cycle parameters for normal (DST$_n$) and fast speed (DST$_f$): CV =Cycle Velocity, CF = Cycle Frequency, PD = Absolute propulsion duration, SwD = Absolute swing duration, PPD = Absolute pole propulsion Duration, CL = Cycle Length, PL = Propulsion Length, SwL = Swing Length, PPL = Pole Propulsion Length (* corresponds to a significant difference between DST$_n$ and DST$_f$ at a level of $p < 0.05$).

		Temporal component				Spatial component			
	CV (m/s)	CF (Hz)	PD (s)	SwD (s)	PPD (s)	CL (m)	PL (m)	SwL (m)	PPL (m)
DST$_n$	4.04 ± 0.38	0.67 ± 0.04	0.20 ± 0.02	0.56 ± 0.06	0.54 ± 0.03	6.04 ± 0.57	0.84 ± 0.08	2.18 ± 0.37	2.13 ± 0.19
DST$_f$	5.36 ± 0.43	0.80 ± 0.05	0.17 ± 0.02	0.46 ± 0.05	0.40 ± 0.02	6.75 ± 0.70	0,89 ± 0.11	2.48 ± 0.35	2.19 ± 0.22
	0.012*	0.012*	0.011*	0.012*	0.011*	0.012*	NS	0.018*	NS
% change	24	16	-23	-22	-35	10	5	9	3

4.4.4.1.2 Relative values

Table 4.6 showed that relative durations (i.e. ratio between the phase duration and the entire cycle duration) of the swing (SwDr) and propulsion phases (PDr) were not significantly different between the conditions DST$_n$ and DST$_f$.

Table 4.6: Mean (± StD) of relative swing phase (SwDr) and relative propulsion duration (PDr) in DST$_n$ and DST$_f$; NS means that no significant differences were observed between DST$_n$ and DST$_f$ for a significant level of $p < 0.05$.

	SwDr (%)	PDr (%)
DST$_n$	37.11 ± 2.87	13.25 ± 1.63
DST$_f$	36.75 ± 2.01	13.5 ± 2.01
	NS	NS

4.4.4.2 Joint kinematic

As reported in study 1, the swing and propulsion phases are the two main periods for the generation of displacement in the DST. Therefore, the range of motion (ROM) of the hip, knee and ankle was analysed in these phases.

During both the propulsion phase and the swing phase, the hip ROMs were significantly increased between normal and fast conditions (figure 4.17), increasing from 56.2° ± 5.6 to 64.4° ± 3.0 and from 66.9° ± 8.2 to 77.1° ± 5.6 respectively. Similarly during both phases the trunk ROM was significantly increased between DST$_n$ and DST$_f$ changing from 6.5° ± 2.0 to 16.7° ± 2.9 for the propulsion phase and from 7.5 ± 3.0 to 12.5° ± 2.5 for the swing phase (figure 4.17).

In contrast, during the propulsion phase, the increase of speed did not affect the ROM of the knee (26.1° ± 4.2 for DST_n and 26.4° ± 5.0 for DST_f) and of the ankle (45.8° ± 6.5 for DST_n and 46.1° ± 5.8 for DST_f). Similarly, the ROMs of knee and ankle joints during the swing phase remained constant between the two speed conditions.

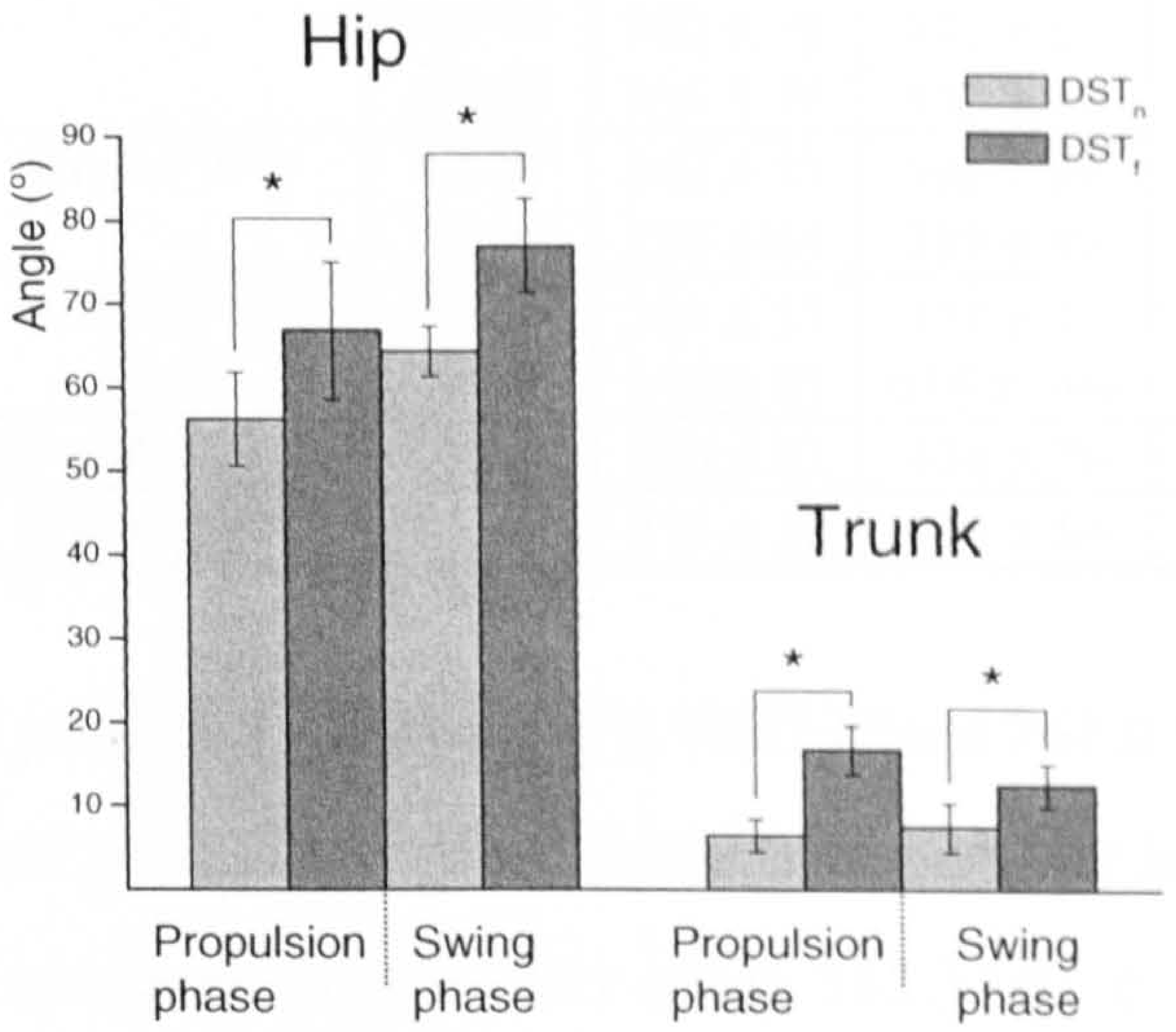


Figure 4.17: Angular ROM of the hip joint and trunk angle for the propulsion and swing phases in condition DST_n and DST_f. * represents a significant difference between the two speed conditions with a significant level of $p<0.05$.

From study 1, it has been reported that the lower limb joints showed flexion / extension sequence during the propulsion phase. To document the mechanisms used for increasing speed, the hip, knee and ankle maximum angular velocity flexion (H2VelF, KVelF, AVelD respectively) and maximal angular velocity extension (HVelE, KVelE, AVelP respectively) were also investigated (table 4.7).

Table 4.7: Modification in the Hip, knee, ankle, shoulder and elbow peaks of angular velocity flexion and extension between DST$_n$ and DST$_f$; S* represents a significant increase of the parameter between speed conditions with a significant level of $p<0.05$; NS means that no significant differences were observed between speed conditions. H1VelF, H2VelF, HVelE, KVelF, KVelE, AVelD and AVel P represents the hip, knee and ankle flexion and extension angular velocity peaks reported in study 1(figure 4.3). SVelE and EVelE represents the extension angular velocity peaks of the shoulder and elbow reported in study 1 (figure 4.6).

		DST$_n$	DST$_f$	
Hip (°·s^{-1})	H1VelF	307 ± 65	412 ± 41	S *
	H2VelF	162 ± 70	171 ± 55	NS
	HVelE	335 ± 79	522 ± 99	S *
Knee (°·s^{-1})	KVelF	242 ± 51	302 ± 69	NS
	KVelE	230 ± 64	317 ± 92	S *
Ankle (°·s^{-1})	AVelD	261 ± 52	353 ± 32	S *
	AVelP	546 ± 81	616 ± 104	NS
Shoulder (°·s^{-1})	SVelE	285 ± 82	424 ± 76	S *
Elbow (°·s^{-1})	EVelE	274 ± 19	446 ± 89	S *

The increase of speed produced a change of AVelD (from 261.0 °·s^{-1} ± 51.9 to 353.0 °·s^{-1} ± 32.1) whereas H2VelF, KVelF remained stable. On the other hand, the absolute value of HVelE and KVelE increased dramatically (from 335.3 °·s^{-1} ± 79.5 to 522.1 °·s^{-1} ± 98.9 and from 230.0 °·s^{-1} ± 64.8 to 316.7 °·s^{-1} ± 92.6 respectively) whereas AVelP remained unchanged (table 4.7).

During the swing phase, the hip angular velocity flexion (H1VelF) was also significantly increased between DST$_n$ and DST$_f$ with values from 307.7°·s^{-1} ± 65.9 to 412.3 °·s^{-1} ± 41.5.

For the upper body, the shoulder and elbow angular ROMs were not significantly different between DST$_n$ and DST$_f$. In contrast, absolute values of the maximum angular velocity extension of the shoulder (SVelE) and elbow (EVelE) were significantly increased (respectively from 285.0 °·s^{-1} ± 81.7 to 424.6 °·s^{-1} ± 75.6 and from 274.3 °·s^{-1} ± 19.5 to 445.8 °·s^{-1} ± 89.4).

4.4.5 Discussion

The objective of study 2 was to 1) describe the kinematic change associated with an increase of skiing velocity and 2) to document the means for increasing speed in the DST.

Between DST$_n$ and DST$_f$, the cycle velocity increased by about 25%. The DST$_f$ average speed was similar to the velocities reported during competitive events (Komi et al., 1982; Norman et al., 1985; Norman and Komi, 1987) or considered as a fast skiing velocity (Gagnon, 1980; Nilsson et al., 2004). These observations showed that the skiers respected the instructions of simulating a racing speed. For DST_f, the mean cycle frequency was lower and the cycle length was larger with comparison to previous findings at a similar speed (Komi et al., 1982; Komi and Norman, 1987; Norman and Komi, 1987; Nilsson et al., 2004) with a range of cycle length between 5.4 to 5.9 meters. Although, previous studies gave little information on the properties of the snow, in this study it may be thought that the larger cycle length / lower cycle frequency values resulted from the quality of the snow with a greater gliding component.

Similar to walking or running (Murray, 1967; Nilsson et al., 1985), the increase of skiing speed was produced by changes in both cycle frequency and cycle length. This was in accordance with the previous study of Roy and Barbeau (1991) but different from other studies (Gagnon, 1980; Nilsson et al., 2004). The studies of Gagnon (1980) and Nilsson et al. (2004) showed only increases in the cycle frequency with a similar proportion of velocity increases in the present study. This structural difference in the observations may result from differences in the experimental set up. In Gagnon and Nilsson et al.'s studies, skiers had 20 meters to reach the desired speed, before entering the recording area. In regard to the 3 to 6 meters cycle length reported by Komi et al. (1982) and Bilodeau et al. (1992) one can question the ability of reaching a stabilised speed with the launching distance used. In contrast, in Roy and Barbeau (1991) and the present protocol (Chapter 3 section 3.3.3), the launching distance was larger than 100 meters, ensuring the development of a stabilised skiing speed.

Temporally, the increase of the cycle frequency induced a strong diminution of the absolute propulsion (PD) and swing durations (SwD). Focusing on the propulsion phase, this result was similar to previous observations on walking or running gaits which found a decrease of the support phase with the increase of speed (Nilsson et al., 1985, Weyand, 2000). It also confirmed previous studies which reported a speed limitation in the DST (Hofman and Clifford, 1992; Smith, 1992; Bellizzi et al., 1998). In accordance with these authors, it can be proposed that the increase of skiing speed may reduce the time allocated for the production of arm and leg propulsion forces. The increase of skiing speed may reduce the duration of the foot is stopped with respect to the ground causing the muscles to progressively work in an inefficient region of the force/velocity diagram (Formenti et al., 2005). Therefore, the maximum speed sustainable in the DST may be physiologically determined. This might explain why skiers prefer to change their technique to a double poling technique on slightly downhill portion. The skiing speed is too large for efficient propulsion using the DST which would lead to a larger mechanical and metabolic cost compared to the use of the double poling technique.

The relative swing and propulsion duration (i.e. swing and propulsion phase expressed as a proportion of the cycle) were constant between DST_n and DST_f. These results contrasted with walking and running gaits where the proportion of swing and support phase durations were modified with increasing speed. These observations confirmed the findings of a recent study in cross-country skiing from Nilsson et al. (2004) who also reported that the temporal structure was an invariant feature of the DST (Schmidt and Lee, 1999). They pointed out the importance it had on the motor control system by simplifying the control of the coordination of the muscles and movement phases with speed. Therefore, the DST locomotion by this temporal invariance constituted an original gait in regard to walking and running. The specific motor program used can be seen as a neural adaptation to the specific environment and material involved in the locomotion. More specifically, the constant relative propulsion and swing phases in the cycle may result from the biomechanical constraints in the DST: namely the gliding phase and the use of poles.

Considering the spatial component of the cycle; the increase of cycle length was associated in the main with an increase of the swing phase lengths. In contrast, the leg and arm propulsion phases remained constant. To understand how skiers spatially increased the swing phase, while keeping the length of the leg and arm propulsion phases constant, the joint angular kinematics of the skiers was investigated. The hip, knee and ankle angular values reported in this study were consistent with data already published in the DST (Gagnon, 1980; Komi et al., 1982; Komi and Norman, 1987).

The analysis of the ROM showed no differences with the increase of skiing speed in the elbow, shoulder, knee and ankle joints. The amplitude of the hip and trunk angles during the propulsion and the swing phase increased similarly between the two velocity conditions DST_n and DST_f. These results supported the idea that the larger hip mobilisation would result from an increase in the amplitude of the trunk angle rather than from a greater mobilisation of the thigh segment. Therefore, the increase of speed may not change the amplitude of the lower and upper limbs.

The constancy in the limbs amplitude in the DST contrasted with walking and running gaits where the increase of speed generated larger angular amplitude of the thigh, knee and ankle in order to increase the cycle length (Nilsson et al., 1985; Milliron and Cavanagh, 1990). We proposed that the limb amplitude invariance in the DST resulted from the presence of the gliding phase. In DST, when the foot contacted the ground it did not experience any braking force that would limit the limbs angular amplitude. In contrast, the gliding phase allowed the limbs to continue their extension and flexion phases.

Another strong characteristic of the DST was the greater angular movement of the trunk at higher skiing speed. The trunk ROM may have a biomechanical role in the DST leg propulsion mechanism. In running, the trunk has been reported to lean forward to keep the ground reaction force in a position to allow forward acceleration (Novachek, 1998). A similar assumption can be proposed to explain the larger trunk ROM in the DST which may position the body centre of mass in a more forward position with respect to the propulsion foot. This may increase the horizontal component of the reaction forces. Since larger propulsion forces are developed to increase skiing speed (Pierce et al., 1987; Millet et al., 1997), in the DST, one may expect the generation of larger horizontal propulsion force, hence the production of larger forward displacement.

From the observation that the propulsion mechanism has been characterised as a sequence of joint flexion / extension (Study 1), this study also analysed the joints angular flexion and extension velocities with skiing speed increase. Whereas the lower and upper limb joint angulations remained stable, increases in the joint angular velocity values have been observed between DST_n and DST_f. This characteristic can be initially viewed as a way to cope with the time reduction of PD and SwD. During the leg propulsion phase, the fact that the hip (H2VelF) and knee (KVelF) angular velocity at flexion remained stable was consistent with previous studies on running (Milliron and Cavanagh, 1990; Kivi et al., 2002). In contrast, the increase of ankle dorsiflexion (AVelD) with speed augmentation constituted a characteristic of the DST locomotion. As the ankle amplitude remained constant between DST_n and DST_f, increase of ankle dorsiflexion (AVelD) with speed augmentation revealed that the ankle was moved into a dorsiflexion position more rapidly. Therefore, the position of the foot for generating propulsion force seemed to be more rapidly executed at higher skiing speed. This was consistent with the fact that the time allocated for generating leg propulsion diminished at higher speed.

During the leg propulsion phase, the hip (HVelE) and knee (KVelE) maximal joint angular velocity extension showed important augmentation with velocity increase. These results were consistent with previous observation on running (Milliron and Cavanagh, 1990). In the DST, AVelD remained constant between the two speed conditions DST_n and DST_f which constitutes a major difference to running (Milliron and Cavanagh, 1990). These authors showed that the ankle plantar flexion velocity increased when velocity increased. The differences between the locomotion characteristics may reflect the constraint of the material and environment on the DST. The ability to increase the angular velocity of the ankle in the DST may be limited by the cumbersome aspect of the skis. In contrast to running, where a vertical elevation and a flight phase of the body can be seen (Dillman, 1975; Williams, 1985), in the DST the leg propulsion produced a forward gliding phase that may limit the involvement of the ankle joint in the propulsion mechanism at higher speed.

The high values of hip and knee angular velocity extension in DST_f showed that the increase of speed in the DST required mainly the solicitation of the proximal joints thus favouring the involvement of the big muscle group such as the gluteus muscles and the quadriceps.

The angular velocity peaks of the hip joint during the swing phase also showed changes. In accordance with running (Milliron and Cavanagh, 1990; Kivi et al., 2002), the recovery of the leg showed an augmentation of the hip angular velocity flexion with velocity increase to match the decrease of the absolute swing phase duration. However, the swing leg may have contributed in the generation of skiing velocity.

Previous observations on the DST showed that the swinging leg transferred some momentum (Gagnon, 1980) or kinetic energy (Komi et al., 1982) to the whole body and therefore increased the speed of the skier. Taking those observations into consideration, an increase of the leg angular velocity will have for consequence to augment the amount of energy transferred to the whole body. Therefore, the swinging leg may contribute to the increase of skiing velocity.

To conclude, in the DST the increase of speed was achieved with 1) a larger involvement of the trunk segment in order to increase the horizontal component of the propulsion forces and 2) a quicker extension phase of the proximal lower limb joint during the propulsion phase. These results suggest that the leg and arm forces responsible for the production of forward displacement were more quickly generated. The DST showed characteristics contrasting with walking and running. The increase of skiing speed did not change the limb amplitude of the joints and the relative phase durations of the propulsion and swing phases. The temporal and spatial invariance in the locomotion may result from the mechanical constraint of the gliding phase.

CHAPTER 5. GENERAL DISCUSSION

5.1 Context of the research and principal results

The DST has been used for thousands of years and is still a popular means of transportation on snow. Nowadays elite skiers can ski 5 km/h faster over the same time than elite runners (Saibene et al., 1989; Bellizzi et al., 1998; Formenti et al., 2005) by exploiting the gliding conditions between the skis and the snow (Formenti et al., 2005).

In contrast to walking or running, where the biomechanical literature for describing the means for progressing along the ground is substantial, the DST locomotion has been incompletely described. Most of the biomechanical studies on DST to date have focused on an inter-subject kinematic or mechanical description of the DST. The analyses of the DST as a sporting activity have mostly described the factors discriminating the skiers of different performance level. Although these data were very interesting, they did not provide much biomechanical information relative to the way skiers produced a technique to progress over the specific ground. The relationship between DST and locomotions such as walking and running has been previously proposed (Street, 1990; Von Duvillard, 2000; Smith, 2003) but requires more scientific bases to be supported.

The specificities of the DST (i.e. practised with skis and poles on snow) questions the type of biomechanical strategies used in order to accelerate the body in those environmental conditions. This type of knowledge would be beneficial for reporting the segmental adaptations of humans to another type of locomotion.

Four studies were undertaken during this work. All of them analysed the DST locomotion of 8 skilled skiers (national level athletes) skiing on a 200 m flat terrain on snow. This protocol was chosen as the first stage for describing the strategies to produce forward movement in the locomotion and for ease of comparison with walking and running.

The first study aimed to describe the common upper and lower joint angular patterns used in the DST with reference to walking and running gaits. During both the swing and stance phases, the lower limb kinematics in the DST was found to be different from the lower limb kinematics of walking or running. Study 1 constituted a first mean to investigate some of the strategies utilised by skier to produce the forward movement of the body. The segmental organisation of the lower body during the propulsion phases showed a flexion extension sequencing in the hip, the knee and the ankle joints. A proximo-distal activation of the three joints was also observed. However, the knee and the ankle angular flexion and extension phases were temporally coupled suggesting the influence of the material (i.e ski) and of the environment (i.e. snow). The propulsion of the arm showed a flexion extension sequencing in the elbow but the co-activation of both shoulder and elbow joints.

Although the kinematic description of the DST (studies 1) provided some interesting insights into the locomotion patterns during propulsion, it did not allow an understanding of 1) the causes of movement and 2) the role played by the joints in the production of forward acceleration. The experimental condition prevented a direct kinetic analysis of the DST, however considerable insight into the causes underlying the observed kinematics can be achieved with an analysis of the energetics of the skier. This was addressed in study 2. Mechanical work and mechanical energy results showed some strong similarities with running. Indeed, in DST there is a large involvement of the elastic structures of the muscle for storage and release of elastic energy. The combination of joint kinematics and BCM mechanics provided a good picture of the implication of joints in the production of movement. The hip was observed to be mostly activated during the first part of the propulsion, when vertical forces are mainly applied (Komi, 1985). The extensions of the knee and ankle joints were supposedly used for the generation of BCM forward velocity.

The biomechanical strategies for generating forward movement in DST have been clearly elaborated within study 1 and 2. DST is practised with poles that may influence the way locomotion is undertaken (chapter 2. section 2.1.4.2). Using kinematic, mechanics and coordination analyses, study 3 analysed the different roles of poles and highlighted their impact in the generation of forward displacement. The results showed that without poles, some subtle kinematic and mechanical changes were observed in the DST movement. Poles may influence the lateral stability of the locomotion but also may affect the coordination of the lower-limb segments during the propulsion phase. Without poles, skiers adopted a compensatory posture which tended to lower position of the BCM.

The generation of speed in DST can be better understood with an analysis of the kinematic changes associated with an increase in skiing speed. With regard to the lack of data in the literature, study 4 constituted a first attempt to understand kinematically how additional cycle velocity can be produced in the DST. Our results showed that the increase of speed was obtained through an increase in both cycle length and cycle frequency parameters. However an increase in speed did not modify the relative proportions of propulsion and swing phase durations (PDr and SwDr) during the cycle. Larger skiing speeds were achieved with an increase of the joint flexion and extension angular velocity peaks in both upper and lower limbs. However the joint ranges of motion remained constant. The trunk segment showed larger angular amplitude at higher speeds. It was suggested that this helped to increase the magnitude of anterior-posterior forces during propulsion.

With regard to the whole of the results obtained from this work, their contribution to the characterisation of the DST locomotion can be presented on several levels. A first body of data may be particularly directed to scientist interested in the DST. The experimental results provided some further understanding on the strategies used for the generation of forward velocity. This work constitutes also an attempt to highlight the implications of studying the DST for the development of new theoretical knowledge on the adaptations of human locomotion to a novel environment.

5.2 Contribution to scientific knowledge in the DST

In preamble, this work attempted to characterise the DST with reference to other human forms of locomotion such as walking and running. In this research the DST cycle has been divided into a swing and a stance phase to make easier comparison with these classical human gaits. Further analysis in the stance phase highlighted the "loading" and the "generation" phases within the propulsion period (study 2).

Study 1 provided a global kinematic analysis of the DST, with angular displacement and angular velocity patterns of the main joints analysed in the locomotion from 8 subjects. This is in contrast to previous studies where only 2 subjects were analysed (Komi et al., 1982). The larger sample size showed some strong inter-subject consistency in the kinematic and mechanical patterns. As a contribution to the DST literature, the results of this work addressed and provided insights on 2 different topics, these being; 1) propulsion mechanisms involved in DST, and 2) the mechanisms for increasing speed in the DST.

5.2.1 Propulsion mechanisms involved DST

The leg propulsion phase has been reported as rather complicated because it is mediated through skis. The skier must allow a grip between the grip wax and the snow. Such requirements suggested that the generation of forces onto the ground is specific to the DST activities and therefore that the propulsion mechanisms are particular too if compared to other terrestrial locomotion. The description of the propulsion mechanisms are essential information for the understanding of the techniques used in DST for progressing along the ground.

2.1.1 Lower limb propulsion mechanism

Study 1 exhibited the classical mechanism of leg propulsion with a proximo-distal organisation of the lower limb segments. In fact it has been previously observed that whenever a transfer of joint rotation into translation of body segments is desired, a proximo-distal sequence of the joints has been seen (Van Ingen Schenau, 1989). However, the sequencing is different from that observed in running and jumping, where the activation of the ankle joint is succeeding the one of the knee joint. It was suggested that the result of the cumbersome of the complex ski and shoes which constraint the ankle and restrain its degree of freedom. Indeed, the ankle joint can not be fully plantar-flexed as it can be observed in running (study 1, figure 4.2).

In the DST, the lower limb propulsion mechanism was accomplished through two phases which have been suggested as "loading phase" and "generation phase" (study 2). The former involved an extension phase of the hip joint that be concomitant with the large vertical force applied (Komi, 1985). This phase is of importance in the generation of forward movement as it allowed a grip between the ski sole and the snow, indispensable basis for producing horizontal forces. Hip extensor muscles (e.g. Biceps femoris, Gluteus maximus) are therefore suggested as important muscles groups in the leg propulsion mechanism. However, it is still unknown if the sequencing of muscles activation is related to the level of vertical forces generated during the "loading phase".

During the "loading phase" the extension of the hip was concomitant with the flexion of the knee and the dorsi-flexion of the ankle. Mechanically, this flexion of the lower limb is supposed to gradually increase the horizontal component of the forces vector. The forward acceleration of the body is mainly created during the "generation phase" with a rapid extension phase of the knee and ankle joints, when the horizontal component of the force vector may be at its maximum.

The leg propulsion mechanism showed a flexion (i.e. during the "loading phase") and an extension (i.e. during the "generation phase") sequence of the lower limb joint which has been reported in various activities such running (Komi and Gollhofer, 1997) or jumping (Bobbert and Van Ingen Schenau, 1990; Bobbert et al., 1996). This has been reported to induce a stretch followed by a shortening in the muscle that has been suggested to increase the produced force (Komi and Bosco, 1978). The stretching phase may allow the muscle to build up an active state of force prior to the shortening of the muscle. This would enhance the work generated by the muscle while shortening (Bobbert et al., 1996). The influence of the elastic properties of the complex muscle-tendon in the mechanics of the DST locomotion has been observed in study 2. The calculated mechanical efficiency value (i.e. 0.59) indicated the large intervention of muscle elastic component in the generation of positive work (Cavagna and Kaneko, 1977).

Previous study from Komi and Norman (1987) reported that a stretch-shortening cycle (SSC) existed in the DST comparable to that in running. A recent study (Komi and Gollhofer, 1997) reported that the SSC model was more likely to be observed in running or hopping since the mechanical requirements (i.e. short and fast eccentric phase, immediate transition between stretch and shortening) are specific to these activities. With regard to the time scale separating flexion and extension phases in the joints, approximately 260 ms (Hoffman and Clifford, 1992), it is suggested that a SSC model may not be applicable to DST.

2.1.2 Poles propulsion mechanism

Poles have been reported to generate a rather small proportion of the forces used for forward movement; representing a force rate 30 times smaller than that from the legs (Komi et al., 1985; Pierce et al., 1987; Bellizzi et al., 1998). In addition to the supposition that poles provide additional forces to maintain skiing velocity (Hoffman and Clifford, 1992) during the gliding phase (i.e. to counteract velocity decrease due to snow friction), study 3 reported that poles impacted on the posture of the skier and on the leg intra-limb coordination during the propulsion phase. Observations of the DST_{wp} condition with reference to DST_n showed that the skier's body was more flexed during the swing phase (i.e. mainly during the gliding phase when the skier is primarily supported on one leg only). This posture produced a lower position of the BCM in response to a relatively unstable state during the one leg stance period (Study 3). This emphasised the use of poles as a means for maintaining balance/stability of the skier during the swing phase.

In agreement with previous studies (Hoffman and Clifford, 1992; Smith 1992) study 3 reported that poles influenced the average skiing velocity. Without poles the sizeable decrease in cycle velocity was observed to be achieved largely through changes in the cycle length. This decrease in the cycle length may be the consequence of a diminution of the forces produced by the lower limbs on the ground. Without poles, study 3 reported that the lower limb intra-limb coordination was affected. Indeed during the propulsion phase the lower limb segments were more uncoordinated (i.e. larger out of phase relationship between the segments) in condition without poles. Although more research is required, it is proposed that a relationship may exist between the intra-limb coordination and the force produced for propulsion. If this hypothesis is experimentally verified, intra-limb coordination analysis may constitute an excellent tool to evaluate the quality of the propulsion phase in DST.

From our result (study 3) the case has been made that poles are facilitating or maybe improving propulsion mechanisms and therefore represent an important piece of equipment for the DST locomotion. With poles, the additional supports suggest that less emphasis is placed on balancing the body centre of mass. The system can therefore be reorganised to improve the propulsion mechanisms.

5.2.2 How skiers increased their speed in DST?

The literature provided very few data on the mechanisms involved to increase the skiing speed the exception being Gagnon, (1980, 1981), Roy and Barbeau (1991) and Nilsson et al. (2004). However, these studies analysed only temporal and spatial cycle parameters.

Our results showed that the speed in DST was increased through faster angular activation of the propulsion and recovery limbs. This represents an answer to the mechanical constraints observed in DST when speed increases. In fact in DST, as in running (Weyand et al., 2000) the time available for leg propulsion decreases with the increase of speed (Hoffman and Clifford, 1992; Bellizzi et al., 1998). In other words, the grip between the ski and the snow and the production of horizontal forces had to be generated more quickly to sustain a higher velocity. As a result, skiers were forced to execute the propulsion movements more rapidly, hence the observation of larger joint angular flexion-extension velocity peaks in fast skiing condition (study 4). In mechanics the change of momentum (i.e. product of the mass of the skier with his velocity) is equal to the impulse (i.e. product of the duration of the propulsion phase with the average force generated by the skier for the displacement). As the time available for leg propulsion decreased in fast skiing condition, the only way to produce a change of speed is by modifying the forces produced. Therefore it can be hypothesised that in DST as in running (Weyand et al., 2000) larger skiing speed would require the generation of larger leg and arm propulsion forces.

The angulation of the trunk constituted an important feature of the change in the kinematics of DST with increasing speed that supposed a modification of the propulsion reaction force orientation. The larger flexion of the trunk during the leg propulsion phase may move the body centre of mass forward, facilitating the expression of the horizontal component of the force.

5.3 Implications for coaches and practitioners

In addition to the theoretical insights of the work, several results are of value to coaches in the making of training programs.

Previous studies from Pierce et al. (1987) and Komi (1987) reported that faster skiers were able to generate larger leg propulsion forces. In the light of the previous section, coaches should aim to increase the technical ability of the skier to produce large propulsion forces. With regard to the large involvement of the hip, knee and ankle joints in the propulsion mechanism (study 2), it may be advised that training should seek to strength muscles related to hip extension (Hamstrings, Gluteus maximus), knee extension (Quadriceps, Tensor fascia lata) and ankle plantarflexion (e.g. Gastrocnemius, Soleus and Plantaris). Those muscles have been observed as essential in 1) the generation of a grip between the ski and the snow and 2) the generation of horizontal forces. Large skiing speed came with to a decrease of the time allocated for the leg propulsion (study 4; Hoffman and Clifford, 1992). This muscular ability for producing high force in a short period of time is a factor of performance in the DST and should be developed in the training sessions. Therefore, it is important that some exercises are done with the purpose of recruiting the muscles to a greater extent and faster than in previous training (Rusko, 2003). Considering dry-land training, exercises should be sought that have shorter propulsion durations, longer step lengths and with higher velocity roller-skiing (Rusko, 2003).

The observation of flexion-extension periods in the joints was of value in the scope of determining the type and the intensity of the training to be proposed. As the utilisation of the elastic structure of the muscle-tendons constituted important components in the locomotion as energy-saving mechanism, coaches may be advised to focus on improving the stretch-shortening efficiency of the muscles. In practice, it may be advisable to develop some strenuous explosive-type strength training for the leg on dry land. These may be following plyometric programme composed of variety of jumps such as alternate jumps, bilateral countermovement jumps, drop jumps, hurdle jumps and one legged jumps. One legged jumps may be preferred as they are more specific to the DST activity.

Study 3 showed that skiing without poles may be affecting the generation of forces during leg propulsion (i.e. with a modification of the segmental intra-limb relationship). Coaches may be advised to include training sessions of skiing without poles. This kind of training may increase the work load on the leg forcing the athlete to rely only on the leg for propulsion. With practise, skiers may be improving lower limb coordination and balance skills; although this is still to be confirmed. Ultimately, skiers may develop their ability to produce larger leg propulsion forces. One can expect that international level skiers would show very stable coordination patterns while skiing with or without poles.

The trunk segment is thought to be highly involved in the production of high skiing speed (Study 4). In DST the trunk undergoes larger ranges of angular motion than in walking and running and in general is observed to be in a more flexed position. In addition the trunk seemed to be working alongside the arm to produce larger upper body propulsion forces (Smith, 2003). Skiers therefore could be advised to strength the spinal and abdominal muscles in order to indirectly increase the propulsion forces generated and reduce the fatigue that may be encountered with such a posture.

From a motor learning aspect, we observed that the increase of speed did not modify either the angular joint amplitude or the proportion of swing and propulsion phases in the cycle. In accordance with Nilsson et al. (2004), this suggests that the inter-segment and leg propulsion coordination of the DST can be learned from relatively slow velocities. The learning of efficient DST may be realised with low velocity limb movement and low metabolic consumption. This would reduce the demands on the learners and may suppose the DST to be a relatively easy locomotion to learn and practise.

5.4 Contributions to scientific knowledge on human assisted locomotion

Although this work aimed to describe the techniques used to progress along the ground in the DST, on a broader perspective our results allow a characterisation of the locomotion with reference to human walking and running. As an ancestral locomotion using skis and poles, the DST constitutes a form of human assisted locomotion. It also has the particularity of involving a gliding phase. Therefore, this locomotion provided some knowledge as to the methods humans use to adapt a locomotor pattern to the environment. Our results provided a good ground to consider the DST as an additional locomotion. It was suggested that the DST could constitute another way of investigating controversial topics such as transition gait and locomotor adaptation to environmental conditions.

The value of this work can be summarised by answering the following questions: what kind of locomotion is the DST and how does the skier exploit the gliding environment?

5.4.1 What kind of locomotion is the DST?

This question reflects the concerns of previous authors regarding the characterisation of the DST as an extension of walking or an adaptation of walking or running to a specific environment (Street, 1990; Von Duvillard et al., 2000; Smith, 2003).

The kinematic and mechanical analyses of the DST provided in this work allow a position to be taken over the characterisation of the DST locomotion. The mechanical analysis provided a useful method of describing the overall mechanisms used to progress along the ground. The energy fluctuations of the BCM in DST showed similar patterns to those seen in running, with an in-phase relationship between the kinetic energy (E_{KX}) and the potential energy (E_P) during the propulsion phase. This relationship with running was strengthened by the estimation of a high value of efficiency (i.e. 0.59, Study 4) that revealed the utilisation of the elastic structure of the system muscle-tendon to store and release energy into E_P and E_{KX}.

The resemblance between assisted and non-assisted human locomotions can be also observed between the skating technique of cross-country skiing (chapter 2, figure 2.3) and walking. Minetti et al. (2001a) reported that in skating a pendulum-like mechanism could be responsible for some of the mechanical savings during progression. The same authors conclude that, mechanically, skating resembles walking. These interesting parallels between two varieties of skiing locomotion and walking and running may provide new insights into human gaits.

It is of note that in both running and DST, the time available for generating propulsion force constituted a small proportion of the overall cycle (i.e. 15% and 35 % in 4 m/s DST and running). In contrast to running and DST, in walking and skating, the leg propelles the body during a larger proportion of the cycle (60% for walking; 45 % for skating). The application of force on the ground for a long period in the cycle allows the BCM to rotate about the point of support, acting as a pendulum, however in running or DST, the short duration of the propulsion phase restrains the pendulum like movement so another energy saving mechanisms is used which involves a passive energy exchange between E_P, E_{KX} and E_L. Therefore, the mechanics of overall human locomotion seems to be related to the temporal characteristic of the foot contact on the ground as previously reported in walking and running (Minetti and Alexander, 1997). This observation could open some new hypotheses concerning gait transition theories.

Although, it is still to be empirically shown, subjectively the DST at slow walking pace may be comparable to walking with skis and poles. This implies that at a specific speed, the locomotion changes from a walking pattern to the DST pattern detailed in this thesis. This skiing gait transition may provide additional data for testing the determinants reported to trigger the walking-running transition speed (Margaria, 1976; Hreljac, 1995; Minetti et al., 1994b; Prilutsky and Gregor, 2001; Sasaki and Neptune, 2005).

From the knowledge of the DST gained here, it is possible to propose a determinant for gait transition. As the speed of the skiing increases, the propulsion phase duration decreases (study 1; Nilsson et al., 2004). It may therefore be proposed that at the gait transition speed the duration of the propulsion phase is not enough to produce an effective pendulum motion of the body centre of mass. Hence, it would require a change of the gait segmental organisation with the utilisation of another energy-saving mechanism. Therefore, we propose the foot contact duration or propulsion phase duration as an important determinant of the gait transition in human locomotion.

This is a reasonable hypothesis because 1) the duration the leg applies the forces to the ground has been previously reported as related to the mechanics (Minetti and Alexander, 1997) and metabolic cost (Kram and Taylor, 1990; Bellizzi et al., 1998) of the locomotion and 2) previous authors reported that the gait transition could be triggered by a mechanical and / or metabolic determinant (Margaria, 1976, Minetti et al., 1994b; Sasaki and Neptune, 2005).

It was observed that the segmental organisation in DST during gliding (i.e. flexed knee, extended contralateral hip and arm elevation) was similar to the strategy adopted by humans while experiencing a slip during walking (Marigold et al., 2003). In both conditions, the task is to sustain a controlled forward displacement of the body whilst sliding, keeping the position of the body centre of mass within the base of support. Similar environmental constraints may trigger the same segmental organisation in the subjects. In other words, in human locomotion balance control is dependant on the characteristics of the ground. Since falling from a slip, constitutes a major cause of injuries for elderly people (Gronqvist et al., 2001), DST could be used as an activity to develop / stimulate the balance skill required on a slippery ground. Although the DST may be a relatively easy locomotion to learn, the feasibility for elderly people to practise it needs to be tested and may be dependant on the terrain and sow conditions (preferentially flat slightly uphill terrain with soft snow averagely gliding). It may be relevant to test the balance skills of elderly who have been practising cross-country skiing for some time.

Although the segmental organisation in DST allows an adequate management of the gliding phase imbalance, it also favours the gliding phase to 1) increase the cycle length and 2) decrease of the cost of locomotion when compared to running (Sabeine et al., 1989; Mognoni et al., 2001). In order to develop our understanding of the DST locomotion it appeared necessary to characterise the subject's means to exploit the ground properties.

5.4.2 How skiers exploit the gliding environment?

This work provided some original data to aid the theoretical understanding of the interaction between humans and the surrounding environment. The movement technique detailed in this work represents an advanced DST technique to generate fast skiing speed and reduce the cost of locomotion (Formenti et al., 2005). It was nevertheless dependant on the quality of the snow and of the skis.

On a basic level, the gliding phase allows the increase of the cycle length and the reduction of the cycle frequency. These characteristics have been reported to reduce the cost of locomotion (Saibene et al., 1989; Formenti et al., 2005). In fact, the skier glides with little inter-segment body motion, hence increasing the cycle length free of metabolic cost (Bellizzi et al., 1998; Mognoni et al., 2001).

In addition, the gliding phase allows the use of large joint angular amplitudes over the entire cycle even for low skiing velocities. This has a strong impact on the generation of skiing speed. During the propulsion phase, the large joint amplitude maximised the path over which the limbs apply propulsion forces. These propulsion forces directly acted on the forward displacement making the whole body glide. In contrast with running in which the flight phase replaces the gliding phase, the gliding phase allows a rapid forward displacement of the skier (i.e. rapid increase of E_{KX}) without requiring the elevation of the BCM (study 2). One can propose that in DST the proportion of leg forces involved in the forward displacement of the BCM is larger in comparison to running. In that respect, the gliding phase may increase the propulsion outcome of the locomotion making it more efficient.

During the swing phase, the hyper-extension and flexion of the hip provoke a large angular displacement of the leg. The extended glide allows the recovery of the leg to be done in a relatively straight position while the supporting foot is gliding on the snow. This pendulum movement has been reported as a mean for generating additional speed to the BCM (Gagnon, 1980; Norman et al., 1989; study 2). Indeed the swinging leg has mechanical energy that may be transferred to the rest of the body towards the end of the leg recovery motion. It is supposed that this mechanism may be contributing to reducing the energy cost of locomotion of the DST when compared to running (Formenti et al., 2005).

In relation to the constant joint angular amplitude observed with velocity increases, the gliding phase allows the skier to keep a constant proportion of the phase within the cycle (i.e. SwD_r and PD_r) (study 4). In accordance with Nilsson et al. (2004), the skier used the environment to ease the control of the motor-neural system in the process of increasing speed. Therefore, the technique adopted by the skier may simplify the coordination of the muscle in order to shift the attention load of the nervous system to the regulation of the balance impairment generated by the gliding phase and the limb propulsions.

It can be suggested, then, that skiers exploit the environment in order to reduce the load on the muscular and the nervous systems. Passive energy exchange between the segments and within the BCM are maximised to progress along the ground. We propose that the segmental organisation of human locomotion is mostly driven by the energetics of the activity.

Although the gliding phase increased the performance of the locomotion, it also limits the maximal speed achievable in DST. A continued increase of speed would require the generation of larger propulsion forces. With the increase of gliding speed, the time allocated for the propulsion phase was reduced (study 4, Nilsson et al., 2004). At high speeds (over 7 m/s) the demands of speed contraction on the muscle can be physiological too high so the muscles can not produce large propulsion forces to sustain the increase of speed (Hoffman and Clifford, 1992; Formenti et al., 2005). This mechanical limitation of the DST locomotion has forced the development of additional skiing techniques in cross-country skiing such as the 'double poling technique', the 'kick double poling technique' or the 'skating techniques'. The sideways leg propulsion (i.e. as in ice skating) allows longer time for the generation of propulsion forces, thereby increasing the skiing speed.

5.5 Limitations

The experimental methodology used in this study was chosen in order to maintain an ecologically valid approach and to ensure that the main characteristics of the DST (leg and arm propulsion and gliding phase) were respected. However, the protocol chosen and the external conditions generated noticeable limitations to this work.

In this investigation a recording field of 8 meters was chosen in accordance with the preliminary study (chapter 4, section 4.2) and previous DST studies (Roy and Barbeau, 1991; Bilodeau et al., 1992; Nilsson et al., 2004). In those studies, cycle length values of about 5.5 m were found over a flat terrain and with skilled skiers. Although, the 8 meters recording area was sufficient for the normal speed conditions (DST_n and DST_{wp}), the recording of a full cycle was not possible in the fast speed condition (DST_f) where cycle lengths reached values of 7 meters. It is suggested that the snow conditions at the time of testing offered particularly good gliding conditions that the skiers exploited to reach the high values of cycle length. As a result, the kinematic investigation of the techniques for increasing speed in the DST was made possible only by analysing two half cycles of DST_f coming from two different cycles. The failure to recording a full cycle for the fast skiing speed limited the mechanical analysis of the DST to only the one, lower, speed.

With consideration to this first limitation, future studies undertaking the analysis of fast cross-country skiing speed should be using a different protocol. Fixed cameras were limiting the scope of analysis. Pan-tilt cameras (literature review, section 2.2.2.4) could be a better solution for the recording of a full skiing cycle taking place in a large volume. This technique will also allow a minimal field of view, facilitating the digitising process, hence reducing the experimental error.

The digitalisation by hand was reported as a source error in the data. It was characterised with an accuracy of 5 to 6 degrees depending on the joints (chapter 4, section 4.3.2.2). In the experimental results, the angular changes (i.e. between 6 to 11 degrees) reported between conditions were larger than the digitising error. However, in the case of a maximum error from the digitisation it appears difficult to certify that the angular changes observed are still significantly different. Although the accuracy of the digitalisation may question the validity of the data, all the joint angular changes observed in studies 3 and 4 were concomitant with some modifications in the kinematics of the BCM. However, the error produced with the digitising process represents a strong limitation of the study which should be address in the future through new data collection techniques (e.g. pan-tilt cameras, optical cameras).

The digitising error also had some effect on the pseudo-3D data since a 3% error was reported for any displacement over the 3 different axes (vertical, lateral, and horizontal). As a result, there are some limitations to accuracy of the mechanical calculations. The efforts made in this investigation have led to a first, approximate, global mechanical analysis of cross-country skiing DST. Although the results are far from being considered as final, the observation of the mechanical energy patterns showed curve consistency between subjects. Also, the calculation of the mechanical work used the same program as reported in a series of publications investigating walking, running and skipping (Minetti et al., 1993, 1995, 2001a; Minetti 1998) and the mechanical calculation were consistent with the previous studies that they were compared to. The quality of the mechanical data is highly dependant on the accuracy of the raw kinematic data. Therefore, a thorough mechanical analysis of the cross-country skiing movement will be also dependant on the utilisation of additional experimental techniques.

The number of subjects used (8) may be considered a rather small sample population and although one cycle has been reported to reproduce strictly the segmental organisation of the DST. An increase in the number of subjects or of the number of cycles analysed would have been useful to gain statistically more powerful results. However, the multiplication of the number of cycles would have lead to the inherent multiplication of the amount of digitalisation. Indeed, it will multiply the number of hours spent in the digitising process already quite heavy. It was estimated that for a similar protocol, the adding of 4 subjects undertaking 4 more trials per conditions would sum up to about 200 hours of additional digitising.

The investigation of the propulsion mechanism was only realised with a kinematic analysis. The adding of force and electromyography data would have been appreciated in order to increase our understanding of the leg propulsion coordination and relate the kinematics with the real forces developed on the snow. However, kinetic analyses on snow are difficult and require complex and expensive protocols that in turn lead to many possible additional sources of experimental errors (Komi, 1985; Pierce et al., 1987).

5.6 Conclusions and future studies

The aim of this work was to characterise the biomechanical mechanisms used in DST to progress along the ground in DST. To help answer the question four specific research objectives were formulated.

The first objective was to describe the segmental organisation involved in the DST. Our results reported specific joint kinematic patterns with reference to walking and running due to the environmental and material conditions. It appeared that production of forces during propulsion phase was obtained with a proximal-distal organisation of the lower limb. A flexion-extension sequence of activation of the lower and upper limb joints such as observed in jumping and running activities may be used to increase the generation of propulsion forces. The arm kinematic patterns showed a co-activation of the shoulder and elbow joints.

The second objective aimed to describe the overall mechanics used in the DST to progression along the ground. Similar to a running gait, the use of muscle and tendon elastic component constituted the main mechanisms for saving energy in the locomotion and facilitating the forward movement. This led to the consideration of the DST to be an adaptation of running to a specific environment.

The third objective was to define the role of the joints in the production of forward displacement to the BCM. The combining of mechanical and kinematic data showed the involvement of the hip extension during the first period of the propulsion phase (i.e. gripping of the ski wax on the snow) and the large involvement of knee extensor and ankle plantar-flexor in the generation of horizontal velocity.

The fourth objective aimed to detail the role of the poles in DST. Although, poles did not affect the general structure of the DST locomotion, they were reported to influence the skier's stability during the gliding phase and the lower limb propulsion coordination. Poles tended to increase the gliding phase and improve the segmental coordination strategy during the propulsion phase.

The fifth objective aimed to describe the mechanisms for increasing speed. The increase of speed was achieved with an increase of both cycle frequency and cycle length. At higher skiing speed, the leg and arm joint angles are more rapidly extended whereas the joint angular amplitude and the proportion of the phases within the cycle remained constant. The invariance in the structure of the locomotion was reported dependant on the gliding ability of the DST technique.

The overall conclusion of this work is that although the DST could be related to running, the skiers developed some specific body segmental organisations in response to the properties of the environment and of the material. The DST constitutes a strong example of an adaptation of human locomotion to a constrained environment. Skiers use the ability to glide with the skis, the additional support provided by the poles and the muscle-tendon properties to effectively move along the ground.

A number of further studies are suggested by this work. Although the main purpose of this present study was to report the biomechanical strategies used in the DST to produce speed, it is clear that this work constituted only a first investigation. It would require additional studies in DST to describe the biomechanical (e.g. segmental coordination, muscle activation) patterns for the production of large propulsion forces. Further investigation should be directed towards the understanding of the impact of the material (i.e. skis stiffness and grip wax) on the mechanics of the locomotion. Temporal and spatial electromyography data from the lower limb muscles may be useful data to collect for increasing our knowledge of the leg propulsion mechanism.

In the previous section 5.5 of this chapter, the problems of undertaking biomechanical experiment on an outdoors ski track were discussed. Therefore, the future development of experimental protocols should consider using either new data collection techniques (e.g. pan-tilt cameras) and / or new apparatus (e.g. large treadmills and roller-skis).

Laboratory measurements will open a wide range of new experiment allowing more reliable 3D kinematic data collection. Practically, the use of treadmill and roller-skis may 1) increase the amount of data that can be collected and 2) facilitate the manipulation of the external skiing condition (i.e. speed, cycle frequency, or gradient). However, this would depend upon the mechanical similarities between the DST on snow and the DST on roller-skis.

Section 5.4 reflected the DST as a possible mean for testing the theories related to gait transition in human locomotion. The analysis of the mechanics and metabolic cost of the DST over a wide range of speeds may be of great interest for understanding the locomotion. In addition, a particular attention could be brought to the mechanical characteristics of the DST locomotion undertaken from various levels of expertise.

Section 5.4 also stated the hypothesis that similar segmental strategies were used to manage a gliding phase in skiing to those used by subjects who experienced a slip whilst walking. As a therapeutic purpose, it would be interesting to test the impact of practising cross-country skiing on the balance aptitude of the subject. It may be suppose that DST is a means for increasing the balance skill of people so they could be less subject to balance impairment when walking.

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Abbreviations

AD:	Peak of ankle dorsiflexion
AVelD:	Peak of ankle velocity dorsiflexion
AVelP:	Peak of ankle velocity plantarflexion
BCLP:	Beginning contralateral leg propulsion
BCM:	Body centre of mass
BRLP:	Beginning right leg propulsion
BRPP:	Beginning right arm propulsion
BRPP:	Beginning right pole propulsion
CF:	Cycle frequency
CL:	Cycle length
CV:	Cycle velocity
DST_n:	Diagonal stride technique (normal skiing velocity condition)
DST_r:	Diagonal stride technique (racing skiing velocity condition)
DST_{wp}:	Diagonal stride technique without poles (normal skiing velocity condition)
E_{KX}:	Horizontal kinetic energy
E_P:	Potential energy
ERPP:	End right arm propulsion
E_{TOT}:	Total energy
EVelE:	Peak of elbow velocity extension
EVelF:	Peak of elbow velocity flexion
HE1:	Peak of hip extension 1
HE2:	Peak of hip extension 2
HF1:	Peak of hip flexion 1
HF2:	Peak of hip flexion 2
HVelE:	Peak of hip velocity extension
HVelF1:	Peak of hip velocity flexion 1
HVelF2:	Peak of hip velocity flexion 2
KE:	Peak of knee extension
KF1:	Peak of knee flexion 1
KF2:	Peak of knee flexion 2
KVelE:	Peak of knee velocity extension
KVelF:	Peak of knee velocity flexion
LAE:	Maximum left arm extension
LAF:	Maximum left arm flexion
LAP:	Leg arm propulsion phase
LLE:	Maximum left thigh extension
LLF:	Maximum left thigh flexion
LLP:	Left leg propulsion phase
LSL:	Left ski lift
LSwL:	Left swing leg phase
PD:	Absolute propulsion duration
PDr:	Relative propulsion duration
PL:	Propulsion length
PPD:	Pole propulsion duration
PPL:	Pole propulsion length
RAE:	Maximum right arm extension

RAF:	Maximum right arm flexion
RAP:	Right arm propulsion phase
RLE:	Maximum right thigh extension
RLF:	Maximum right thigh flexion
RLP:	Right leg propulsion phase
ROM :	Range of motion
RSL:	Right ski lift
RSwL:	Right swing leg phase
SSC:	Stretch-shortening cycle
SVelE:	Peak of shoulder velocity extension
SwD :	Absolute swing duration
SwDr :	Relative swing duration
SwL :	Swing Length
Wext:	External Work
Wint:	Internal Work
Wtot:	Total Work