Posture and Visuomotor Performance in Children

The Development of a Novel Measurement System

Ian John Flatters

Submitted in accordance with the requirements for the degree of
Doctor of Philosophy

The University of Leeds
The School of Mechanical Engineering and the Institute of Psychological Sciences

October 2013

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

The following chapters have formed the basis of work submitted for publication in journal articles:

Chapter 1

IJ Flatters, LJB Hill, JHG Williams, SE Barber, M Mon-Williams (2013). Manual Control Sex Differences in 4 to 11 Year Old Children. PLoS One, In Press.

Chapters 2 and 4

IJ Flatters, F Mushtaq, LJB Hill, A Rossiter, K Jarrett-Peet, PR Culmer, RJ Holt, RM Wilkie, M Mon-Williams (2013). Children's head movements and postural stability as a function of task. Experimental Brain Research, Submitted.

Chapter 3

IJ Flatters, P Culmer, RJ Holt, RM Wilkie, M Mon-Williams (2013). A new tool for assessing head movements and postural sway in children. Behavioural Research Methods, In Press.

Chapter 5

IJ Flatters, F Mushtaq, LJB Hill, RJ Holt, M Mon-Williams (2013). The relationship between postural stability and manual control in children. Experimental Brain Research, Submitted.

Appendix

The candidate was awarded an EPSRC funded grant during a three-month suspension of study in the first year of the PhD. The published work arising from this work has been included as an appendix to the thesis:

IJ Flatters, RJ Holt, RM Wilkie, GP Bingham, PR Culmer, B Henson, M Mon-Williams (2012). Predicting the Effect of Surface Texture on the Qualitative Form of Prehension PLoS One.

Acknowledgements

First of all, Mum and Dad. I would like to thank you for your support, particularly during this latest process, but in supporting me in every decision I have made up until now (the offer of the Mediterranean cruise still stands - funding permitting). Thanks also to Anna, Deb and Phil for their encouragement and assistance.

I would like to extend my gratitude to my supervisors, Mark, Richard and Ray and the PAC group (everyone). Faisal and Liam should be singled out in the thanks they receive for their timely help in getting me across the line with this thesis.

Abstract

The aim of this thesis was to develop and test a platform which was capable of measuring the developmental trajectory of postural stability and fine motor control. Moreover, the thesis set out to explore the interdependence of these motor processes through synchronous measurement of postural and fine-motor control processes.

The thesis introduces an objective, fine-motor measure sensitive enough to detect gender differences in children. This system was developed further to incorporate measures of postural sway, providing objective measures of postural performance that were capable of detecting age-dependant task-based manipulations of postural stability.

Further development of the platform to incorporate low-cost consumer products allowed the cost barrier to large-scale measurement of posture to be addressed. This meant that accurate, synchronous and objective measurement of postural control and fine-motor control could take place outside of the laboratory environment.

The developed system was deployed in schools and this allowed an investigation into the effect of seating on postural control. The results indicated that (a) seating attenuates the differences in postural control normally observed as a function of age; (b) postural control is modulated by task demands.

Finally, the relationship between postural control and fine-motor control was investigated an interdependent functional relationship was found between manual control and postural stability development.

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Abbreviations

A/P	Anterior/Posterior
ADL(s)	Activities of Daily Living
BoS	Base of Support
BOTMP/BOT-2	Bruininks-Oseretsky test of Motor Proficiency/2nd Edition
CKAT	Clinical Kinematic Assessment Tool
CoM	Centre of Mass
CoP	Centre of Pressure
DCD	Developmental Coordination Disorder
GRF	Ground Reaction Force
HM	Head Movement
IR	Infra-Red
M/L	Medial/Lateral
MABC/MABC-2	Movement Assessment Battery for Children/2nd Edition
MLM	Multilevel Linear Model
MMT	Maastrichtse Motoriek Test
MT	Movement Time
NJ	Normalised Jerk
PA	Path Accuracy
pPA	Penalised Path Accuracy
RMSe	Root Mean Square Error
SD	Standard Deviation
SDGWN	Standard Deviation of Gaussian White Noise
SEM	Standard Error of the Mean

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General introduction

Childhood development is associated with the acquisition of an astonishing number of skilled behaviours. One reasonably well documented example of a skill acquired over childhood is the ability to accurately direct gaze to stationary and moving targets - a skill that requires the coordinated movements of the head and eyes (Guitton and Volle, 1987). Another example is the acquisition of postural control, whereby an infant who regularly falls over develops into an adult who can maintain stable posture for prolonged periods of time (Hatzitaki et al., 2002; Hayes, 1982). The ability to move the hand skilfully in tasks such as reaching-to-grasp is likewise refined over the developmental trajectory (Schneiberg et al., 2002). Observation over long time periods of any of these behaviours - gaze, posture or hand control - suggests a steady 'linear' progression of the skill across childhood. Nevertheless, inspection of the behaviour over shorter time periods suggests a far more chaotic situation where skills are acquired but can disappear before re-emerging (Kirshenbaum et al., 2001).

One reason that individual skills do not show an inexorable march towards excellence is because they do not develop in isolation, but rather require the development of other underpinning skills. For example, manual skills require accurate visual information so that execution errors can be detected and corrections implemented. Visual information is directly linked to the steadiness of the head (Oullier et al., 2002; Wade and Jones, 1997; Wann et al., 1998) which in turn is determined by the stability of the postural base (Schärli et al., 2012; Schärli et al., 2013; Stoffregen et al., 1999). Similarly, poor postural stability will place an upper limit on the precision with which arm movements can be controlled, meaning that the development of improved manual skill must await better postural control (Haddad et al., 2012). It is reasonable to suppose that the need for better manual skill acts as a driver to the postural system, which might explain why posture becomes increasingly stable over childhood once the basic level of ‘not falling over’ has been reached. It seems clear that carrying out skilled actions requires a synergistic relationship between the development of head, hand and postural control and therefore a complete picture of childhood development requires a consideration of how control of head, hand and posture develop in combination with one another.

This thesis investigates new ways of measuring postural stability in order to assess the developmental changes that occur to postural control, and the interaction between visuomotor tasks, seating support and postural control in children.

Fine-motor skills

Humans skilfully interact with dynamic, changing environments, an ability that is testament to the ability of the central nervous system to rapidly process complex and noisy perceptual information, in order to achieve exquisite motor control (Faisal et al., 2008). Consider the simple act of reaching to a cup and lifting it. From a control perspective, this act requires mastery of a huge number of degrees of freedom (Turvey, 1990). If one considers the biomechanical chain alone (not including the muscles) that has to be controlled in order to achieve this, then the number of solutions afforded by the degrees of freedom at the shoulder, elbow and wrist combined generate vastly more solutions to the control problem than is required (Latash, 2012). However, successfully generating movements at the extremity is contingent on the availability of a stable base of support on which to perform - in this case a reaching action. The trunk must be stabilised to achieve balance and a foundation on which reaching movements are to be performed. The shoulder girdle must be coordinated with respect to the trunk, the arm coordinated with the shoulder girdle, and so on (Kaminski et al., 1995). The ability to integrate these processes into coherent movements is fundamentally important in the social, physical and cognitive development of a child (Piek et al., 2008). Therefore, it is critically important to identify children at risk of developmental delay not only through observation of the development of fine-motor ability (observing the performance on the task itself), but also the gross-motor functions that underpin those movements (Sugden, 1992).

The motor control literature often differentiates between ‘gross’ and ‘fine’ motor control. The term ‘gross-motor’ control is used generally to describe activities involving locomotion and movement of the torso (e.g. walking, maintaining postural stability) whereas ‘fine-motor’ control is associated with tasks that typically involve some form of manual manipulation (Malina, 2004). The measurement of motor performance development in children often relies on norm-referenced, questionnaire-based assessments (Cools et al., 2009) of both fine and gross motor control. These questionnaires represent a valuable tool for assessing movement skill across a range of activities of daily living; however, they have typically been developed to identify motoric development deficits. Of the seven most commonly used battery tests most commonly used in European countries, only five have dedicated fine-motor skill assessment components: the Motoriktest für Vier-bis Sechjärige Kinder (MOT 4-6), the Movement Assessment Battery for Children (MABC-2), the Peabody Development Scales (PDMS), the Maastrichtse Motoriek Test (MMT) and the Bruininks-Oseretsky test of Motor Proficiency (BOT-2). Of these, only two tests are not focused toward the identification of specific developmental problems (Cools et al., 2009) and as such are suitable for the assessment of fine-motor skill in non-clinical populations of children at primary school age: the MABC-2 (Henderson et al., 2007) and the BOT-2 (Bruininks and Bruininks, 2005). In measuring fine-motor performance, the MABC-2 facilitates calculation of normative performance for each participant based on manual dexterity, throwing/catching and balance subtests. The subtests are age-adjusted to enable calculation of norms across three age bands: 3 to 6 years, 7 to 10 years and

11 to 16 years. The BOT-2 consists of four fine-motor or manual dexterity subtests out of eight subtests that comprise the complete battery. From these subtests, separate composite scores are calculated for fine-motor and manual coordination for normative comparison.

The reliability of these tests in the identification of children at risk of movement problems has been demonstrated (Schoemaker et al., 2012; Ellinoudis et al., 2011). However, their application to the field of typical motor development is relatively limited. Firstly, the MABC-2 has age-normed tests which precludes comparison across age ranges. Secondly, the metrics used to index ability are typically subjective or summative. Similarly, absolute measures of task performance used in the study of motor ability, such as the number of successful catches completed in a certain time window (Davids et al., 2000), or pegs placed in holes (Immerman et al., 2012; Poole et al., 2005; Rosenblum and Josman, 2003; Smith et al., 2000) are not capable of investigating the constituent spatial or temporal components of those movements, or how those components develop during progression to adult-like ability. Limitations common to all pen-and-paper type tasks include subjective scoring techniques, poorly defined outcome measures and confounds produced by different task strategies (Culmer et al., 2009).

An alternative approach to measuring the development of manual control involves the utilisation of digital tablets to record participants' movements. This provides researchers with the ability to obtain a range of kinematic and accuracy measures at scales, pertinent to handwriting or other school-based tasks. The main advantage is the speed, simplicity and accuracy of the measurement provided. In addition, the tests are usually conducted by applying pressure to a digitising surface through a film overlay of the task that the participant is required to reproduce. The fidelity of the digitising tablets facilitates quantitative assessment of fine-motor skills such as handwriting and self-paced drawing activities (Miyahara et al., 2008; Rueckriegel et al., 2008; Mergl et al., 1999; Pellizzer and Zesiger, 2009) as well as more dynamic movements such as aiming and serial aiming tasks (Adam, 1992; Haaland et al., 1999). The tasks performed on these platforms map well onto those tasks which are fundamental to school progress (Culmer et al., 2009; Miyahara et al., 2008; Pellizzer and Zesiger, 2009). By analysing the kinematic profile of these movements, it may be possible to identify specific components of the movements that are contributing to drawing errors.

Using the touch-sensitive screen of a tablet PC as an input device, Culmer et al. (2009) developed a platform on which participants interacted with rendered sprites. The sprites themselves could be static (for example a path along which the participant was instructed to trace) or moving (for example, a dot moving over the screen where the participant was instructed to track it with their stylus) and the participant’s response to the stimuli could be measured at a high rate (120Hz) and spatial accuracy. The resulting pen position data could be analysed using the same powerful kinematic measures used in conventional motion capture studies that could describe the spatial and temporal structure of the stimulus response. The sensitivity of this system and its ability to detect subtle effects of gender on motor development are demonstrated in Chapter 1.

Posture

Posture control is essential for humans interacting with their environment and forms the basis of locomotor control, moving oneself through the world when walking or running (Massion, 1998). But even before the developmental stage of locomotion, gaining control and maintaining stability of the head and the body are essential components of carrying out more skilled tasks. The human nervous system requires a stable base in order to develop accuracy and precision in manual control tasks (Colangelo, 1993; Bertenthal and Von Hofsten, 1998).

Upright stance in humans is often modelled as a series of linkages, with joints at the ankle, knees and hip and a mass representing the Centre of Mass (CoM) of an individual balanced on top (Winter, 1995). Without any form of control, this arrangement would simply collapse in the direction of gravity; however, torques at the ankle, knee and hip joints serve to stabilise the CoM in space. The base of support is a crucial concept in interpreting postural stability as it represents a limiting space over which Ground Reaction Forces (GRFs) can stabilise the CoM, enacted by torques along the postural chain. In upright stance, the Base of Support (BoS) would be the region enclosing a person’s footprints, as this is the spatial extent of where corrective forces can be applied in response to postural movement. In quiet stance, the shear component of the GRF vector is small (typically <1N in quiet stance) in comparison to the vertical component; thus for the purposes of postural measurement and modelling, only the vertical component of this force is considered (Winter et al., 1998; Morasso and Schieppati, 1999). The spatial location of the vertical component of the GRF on the support plane is commonly referred in the literature as the Centre of Pressure (CoP). In a perfectly balanced upright posture, the CoP would lie directly under the CoM in the direction of gravity but, given the instability of the arrangement, this is never the case in practice (Winter, 1995). Small displacements in the CoM arising from breathing (Bouisset and Duchene, 1994) or circulation (Conforto et al., 2001) maintain the postural chain in a continuous state of flux, transitioning between temporary, imperceptible toppling of the CoM and small corrective postural adjustments which act in opposition to the tendency of the CoM movement to regain stability.

The timescales on which this control process operates are short enough that, even in upright stance, deviation of the CoP over a 20s period can be enclosed within a circle 12mm in diameter (Prieto et al., 1996) - extremely small in comparison to the height of a typical individual.

Thus, the postural chain can be considered as a dynamic system, inherently unstable with continuous displacements of the CoM being constantly countered with corrective postural movements (Winter, 1995). Deficits in the magnitude or timing of the corrective postural response could result in a situation where the CoM is displaced beyond the limit of the base of support. In this instance, balance will be lost unless a corrective step is taken to increase the size of the base of support. Motor batteries typically quantify postural stability by measuring the time taken for this situation (loss of balance or the onset of a corrective movement) to occur in a destabilised posture, for example walking forward on a line or standing on one leg on a balance beam (Bruininks and Bruininks, 2005). An individual with poor postural control will be more likely to lose balance sooner than a person with optimal postural control. This time to balance loss metric therefore provides a crude measure of postural stability which is easy to implement, requires no special equipment and can be norm-referenced to provide an indication of an individual's postural stability in relation to the population.

While tests such as these may be sufficient to detect children at risk of gross-motoric deficits (Wiart and Darrah, 2001), the measure cannot quantify performance unless balance is lost, thus lacking the fidelity of CoP measures of posture, where numerous metrics can be applied to the CoP to quantify stability.

CoP measurement is a powerful tool in the field of studying postural development, as this single measure captures postural movements and their net effect on the CoG. This displacement in the CoM is indirectly observable at the BoS by a displacement of the CoP. CoP movement data, and the resultant metrics generated from it, have the sensitivity to detect subtle developmental trends in postural control (Kirshenbaum et al., 2001; Riach and Starkes, 1993; Riach and Starkes, 1994; Rival et al., 2005; Schärli et al., 2013), manipulations of sensory feedback (Barela et al., 2003) and sensory re-weighting (Bair et al., 2007; Rinaldi et al., 2009; Woollacott et al., 1986), and gender (Smith et al., 2012). The gold-standard measure for postural performance is the use of clinical-grade force platforms to quantify CoP movement (Winter, 1995). In their various forms, these devices have been successfully used in the analysis of postural sway for the past 30 years and have demonstrated sensitivity to subtle neurological or physiological contributors to differences in sway. The devices used in clinics achieve such sensitivity through extensive setup and calibration procedures, with the device inset into the floor of the laboratory, facilitating their use in gait analysis.

Manufacturers such as AMTI and Kistler provide more portable variants of these clinical force platforms. Systems such as the 9260 series force platforms (Kistler, Amherst, NY, US) and the AMTI AccuSway (AMTI, Watertown, MA, US) provide highly accurate balance measurement outside of the laboratory setting and are specifically developed for the measurement of postural behaviour. In purely practical terms, the ability to deliver accurate, quantitative assessment of balance performance to the individual is a great advantage. Furthermore, if the devices are embedded within concentrations of the populations that are of interest to the researcher, then they represent a time-effective, efficient method of acquiring a rich dataset. In clinical use these devices are therefore a great asset to researchers as they can reside in a doctor’s surgery, or in specialist falls clinics. While their efficacy is supported by a swathe of studies demonstrating the assessment of posture across a range of populations and pathologies, their widespread use remains somewhat limited.

By definition these devices are portable, such that they are not permanently mounted in a laboratory floor, but their use outside the controlled setting of the laboratory is limited by numerous other factors relating to their setup. The devices typically require an external power source, which introduces limitations on where the devices can be placed. Furthermore, the devices could be sensitive to factors relating to the environment in which they are placed. Using these devices on compliant surfaces could introduce a measurement error owing to the nonlinear, unpredictable distribution of force between the peripheral load cells used to calculate the CoP.

Most portable force platforms typically require external hardware to amplify the signal from the force sensors in the platform (although the AMTI device amplifies the signal internally). Although the use of cables to power the setup and transmit signals to the host computer is a relatively minor inconvenience when using the equipment in-situ, the cost of the devices remains the biggest hurdle in their widespread deployment outside of the lab environment with a complete setup typically costing in the region of £15,000 including the amplifier and cables (McDermott, personal communication).

Cost-effective CoP measurement

Despite the previously highlighted limitations to portable devices, there remains a requirement for cost-effective, fully portable, postural measurement devices. Novel work by Clarke et al. (2010) appeared to offer a solution which achieved this. By using off-the-shelf, consumer electronic equipment, the WiiFit (Nintendo, Kyoto, Japan), Clark et al. (Clark et al., 2010) were able to demonstrate that, as a postural measurement device, the WiiFit was as sensitive to a conventional clinical force platform using widely adopted posturographic measures. This initial publication has resulted in numerous studies into the efficacy of the WiiFit board in posturographic measurement, both by quantifying the absolute positional accuracy of the CoP measurement (Bartlett et al., 2013), and comparing posturographic measures from the WiiFit to clinical equipment (Holmes et al., 2013; Huurnink et al., 2013; Young et al., 2010). While these studies favour the application of the WiiFit to postural measurement, some authors advise caution when drawing comparisons between what is essentially a gaming device, and clinical force platforms which are classed as medical devices (Pagnacco et al., 2011) and regulated and validated accordingly. Pagnacco, Ogero and Wright (2011) highlight two principle limitations with the WiiFit in the context of using its posturographic measures in the clinical setting. First, clinical-grade force platforms have been developed to be as accurate as possible both in terms of the sensitivity of the constituent force-measuring components and in terms of data synchrony. The latter point is of critical significance, even in the most basic of setups where the force platform calculates the CoP from the weighted contribution of the four load cells in the platform.

From Clark et al. (2010), the equations used with the WiiFit to calculate CoP in the medial/lateral direction (CoP_x) and the anterior/posterior direction (CoP_y) are shown in equations (1) and (2) respectively:

$$CoP_x = \frac{0-F_{TL}-F_{BL}+F_{TR}+F_{BR}}{F_{TOTAL}} \qquad (1)$$

$$CoP_y = \frac{0-F_{BL}-F_{BR}+F_{TL}+F_{TR}}{F_{TOTAL}} \qquad (2)$$

Where F_{TL} is the most anterior, left sensor from the participant’s perspective, F_{BL} is the most posterior, left sensor and F_{TR} is the most anterior, right sensor from the participant’s perspective, F_{BR} is the most posterior, right sensor. F_{TOTAL} is the summed force measured across all four sensors. This results in a unitless dimension in the Anterior/Posterior (A/P) and Medial/Lateral (M/L) directions which is multiplied by a predetermined calibration factor as per Clarke et al. (2010, Appendix A).

The WiiFit device offers no programmatic control over when the transducers are polled for their values. Thus the interval over which the force transducers are sampled are subtly inconsistent, i.e. the force signals contain jitter. It can be seen from equations (1) and (2) therefore that if transducer values from different time points are used to derive the X (M/L) and Y (A/P) coordinate of the CoP, then this will be a potential source of measurement inaccuracy. For posturographic studies, the low frequency of the signal of interest (and resulting filtering to ~ 5Hz) in comparison to the capture rate (~ 60Hz) limits the effect of this component of measurement inaccuracy.

Secondly, quantization noise has long been known to affect postural measures (Granat et al., 1990; Schmid et al., 2002), but the noise characteristics of the WiiFit device have, until only recently, been reported in detail (Huurnink et al., 2013; Pagnacco et al., 2011). These studies confirm that a characteristic feature of the quantization noise of the Nintendo WiiFit is that it is inversely proportional to the mass being measured. Therefore, not only is there a problem associated with quantization noise on spatio-temporal measures, but more seriously, the signal to noise ratio of the device changes as a function of the mass applied to the platform (Pagnacco et al., 2011). This has serious implications in the investigation of posture control development as the mass of the participant could be a confounding variable in the generation of summary spatio-temporal postural measures (such as CoP velocity).

Finally, the WiiFit board does not calculate the moment of forces about the CoP, i.e. it can only resolve the vertical component of the GRF. As stated previously, the low shear forces present in quiet standing measures of postural behaviour mean that the position of the vertical component of the CoP approximates well to one determined through clinical force platforms (Clark et al., 2010; Holmes et al., 2013; Huurnink et al., 2013; Jorgensen et al., 2013; Wikstrom, 2012). Thus, the inability to determine the moment of force generated at the CoP precludes its use in more dynamic activities where shear forces form a larger component of the GRF.

The WiiFit board therefore represents a potential solution to the problem of measuring postural stability outside of the laboratory environment. However, in populations where mass varies as a function of age, it is critical to implement effective filtering methods to address the effect of quantization noise on the signal and avoid the confounding effect of mass on spatio-temporal measures of CoP behaviour. In Chapter 3, an analysis method is described which addresses the challenges associated with using the WiiFit device in developing populations.

Head movement measurement

In addition to using CoP to approximate CoM position, analysing postural sway at the head can provide a measure of postural stability. The inverted pendulum model of postural control would suggest that the gain of any sway present in postural control would be larger at the head (Winter et al., 1996), with head movement during quiet stance has been shown to be sensitive to subtle visual (Chang et al., 2010; Wann et al., 1998) or somatosensory manipulations (Jeka et al., 1997).

The control of head orientation is of critical importance when interacting with the environment (Assaiante and Amblard, 1995), and the ability to stabilise the head in space is critical for skilled development (Thelen and Spencer, 1998). Visual tracking tasks could conceivably displace the CoM of the individual as it is known that individuals can visually track a target using just their eyes but such tracking often involves head movements (Stoffregen et al., 2006).

Furthermore, it is well established that visual information plays a role in the maintenance of postural stability; this role for vision is greater in younger children (Assaiante, 1998; Hatzitaki et al., 2002; Lee and Aronson, 1974; Shumway-Cook and Woollacott, 1985; Sparto et al., 2006; Wann et al., 1998) and with visual tracking tasks, differentially affecting postural stability in young children (Schärli et al., 2012; Schärli et al., 2013).

Considering the developmental effects observed in postural stability, specifically movement of the head (i.e. gaze), measures of head movement could compliment measures of postural stability such as CoP. The relative contribution of vision to postural stability could be considered, but only in the presence of a measure for both overall stability (CoP) *and* head movement.

By measuring the destabilising effect of gaze in children, it is possible to investigate how the naïve postural control system is affected by visual task demands.

There are various techniques in the literature for measuring postural sway at the head and, as with CoP and the lab-based force plates, these are primarily lab-based technologies. One approach is to use a magnetic motion capture system (such as the Ascension ‘Flock of Birds’ system) that derives a 3D position from a magnetic field in three orthogonal planes (Welch and Foxlin, 2002). These systems have the advantage of being light and compact so they can be readily placed on the head (though the cables can interfere with head movement). There are two disadvantages with these systems. First, they are expensive and require a degree of technical competence in the user. Second, the systems are sensitive to ferrous or conductive objects, as these disturb the magnetic field within which the sensors operate. The system can be calibrated to account for simple static ferrous objects, but in less controlled environments (e.g. schools) this is impractical due to time limitations. Finally, the use of optical motion capture systems would provide highly accurate positional data over a large number of points and over a large measurement volume. One of the principal advantages of the optical motion capture systems is their ability to operate wirelessly, which reduces measurement interference and reduces the risk of accidental damage of the equipment.

In addition, some systems are portable and can be calibrated in-situ to varying degrees of resolution. The main disadvantages of using equipment of this type outside of the laboratory setting is that the equipment is complex to set up, costly and requires a relatively large amount of space in which to operate. The calibration of the portable optical motion capture systems is also extremely sensitive to accidental shifts in camera position during testing, something that is difficult to guarantee when testing children in a relatively uncontrolled environment.

Portable systems

Inertial motion capture systems have been developed to incorporate micro-electronic accelerometers and gyroscopes, and can be made small enough to be worn on the head (Zhou and Hu, 2008). These systems typically use three orthogonal accelerometers to specify an acceleration vector that is transformed into a consistent (typically gravitational) frame of reference using data from three gyroscopes. There is a question about whether the rotational data provided by inertial sensors is optimal for measuring head movements. The difficulty is that rotational head movements caused by sway around the ankle subtend only a few degrees and may therefore be less sensitive than head translation in detecting subtle changes in sway. One way to obtain displacement measurements would be to integrate the accelerometer signals twice, enabling crude calculation of positional data. However, the low signal/noise ratio (owing to the low velocity of the sway motion) combined with a twofold integration yields inaccurate results. Chapter 3 presents a direct comparison of two portable technologies used for head movement measurement, which would complement the CoP method described previously for postural analysis.

The requirement for a low-cost system

When capturing human movement, equipment cost is a key determinant of the scalability of the system and typically prohibits large-scale study of motor behaviour outside of the laboratory setting. A typical, portable motion capture system used in the clinical will typically cost in the order of £8,000 per camera; in a 10 camera system this represents an outlay of £80,000. With the addition of a force platform (£15,000) and its requisite amplifier, the total cost will ordinarily exceed £100,000 (McDermott, personal communication). However, these systems are highly accurate and capable of resolving positional data over several cubic meters to millimetre accuracy or better. Posturography can be considered to be a specific subset of motion capture and it is one which does not necessarily require large capture volumes, as the volumes subtended by body segments of interest in quiet stance is small in relation to gait, for example. The minimal measurement volume required permits consideration of simpler, cheaper solutions when studying postural stability. Addressing the cost of a postural measurement system permits large-scale, in-situ study of postural stability and could provide valuable insight into how it develops and varies over time.

Such low-cost systems have been previously developed using the Nintendo WiiMote platform, whereby Infra-Red (IR) cameras housed within the controllers (designed to enhance gameplay human/machine interaction) are deployed as a single stereo pair, and calibrated to determine the parameters required for the stereo triangulation of an IR point source in 3D space.

The WiiMote controllers are well adapted to a motion capture application, as on-board hardware resolves the image on the camera sensor and uses band-pass filters to generate a binary image, from which the IR sources are isolated as discrete image regions or ‘blobs’. On-board processing identifies the centroid of the IR ‘blobs’ on the camera image and 8x sub-pixel filtering yields an effective resolution of 1024 x 768 from a 128 x 96 sensor for the IR source coordinates (WiiBrew, 2011). Using Bluetooth connectivity, only the coordinate data is transmitted from each WiiMote, avoiding obvious limitations of having to trail wires about the workspace, but also vastly reducing the bandwidth required when transmitting coordinate information. As no image is transmitted, high capture frame-rates are achievable over the wireless connection. Previous low-cost stereo motion capture systems have been created as a platform for human/computer interaction (Modroño et al., 2011; Scherfgen and Herpers, 2009). Owing to their necessarily large measurement volume (to capture the extent of relatively large gesture movements) the accuracy of WiiMote derived systems, although comparable to more expensive bespoke equipment (Hay et al., 2008), is correspondingly low in comparison to clinical-grade systems when operating over larger volumes. Kim et al. (2012) have developed a setup using the WiiMote devices to track head rotation. The stereo calibration of this setup is performed by illuminating a 3D matrix of LEDs in two camera images, four at a time (the maximum each camera can resolve) to generate a mapping between pixel coordinate pairs (corresponding IR points in two camera images) and their interpolated position in a world coordinate system. Using this method they were able to calculate head rotation in three planes using four IR LEDs resolved at a reported spatial resolution of 1mm.

The measurement of head movement in quiet standing would require a small measurement volume. By exploiting the relationship between measured volume and accuracy, the WiiMote-derived motion capture system could be optimised for small measurement volumes, similar in principle to how clinical-grade equipment can be reconfigured to measure small volumes at sub 100µm accuracies (Windolf et al., 2008). Furthermore, the accuracy of the measurement could be increased sufficiently to enable sensitive detection of head movements and changes across the developmental trajectory. For the purpose of measuring static sway, a single IR source positioned on the head is sufficient to describe the magnitude of sway. With the emergence of the WiiMote-based motion capture systems in the literature, it was clear that these systems were capable of accurate measurement of points across a small volume displacement. Chapter 3 introduces this platform as a solution to the measurement of postural sway in children, avoiding limitations such as cost, portability and ferromagnetic disturbance. Furthermore, the calibration routine developed addresses the limitations of the type adopted by Kim et al. (2012) and facilitates calibration across varying volumes. Chapter 4 reports the development of the system for use in three-dimensional tracking of head displacement and rotation, in situations where the task drives head movements (Schärli et al., 2012). Chapter 5 demonstrates the large-scale deployment of a standalone head-sway measurement device using this platform.

Synchronous gross and fine-motor measurement

The advantage of pen-on-paper, battery-based tests of motor development lies in their ability to be administered in-situ and assess a broad range of movements, with the tests typically comprising gross balance and fine manual dexterity components. The tests do not require expensive laboratory equipment (beyond the cost of the tests themselves) and in most cases can be set up in a relatively short time period for intensive testing of large numbers of children (Bruininks, 1978; Bruininks and Bruininks, 2005; Henderson et al., 1992; Henderson et al., 2007). The limitations of these tests are that they rely on trained personnel to administer the tests, and the measures typically rely on the experimenter’s subjective assessment of task performance. Notwithstanding these limitations, the power of the battery tests lies in their ability to compare an individual’s performance against a normative dataset and across a wide range of tasks (Cools et al., 2009). Thus, in chapter 2, I introduce a system which sought to address the limitations of traditional pen-on-paper batteries (qualitative assessment of movement performance) and exploit the advantages of their application (the ability to deploy the tests in-situ). By developing a system capable of measuring fine-motor movement with the precision of motion-capture-based kinematic measures, and simultaneously obtaining measures of stability and head movements during the tasks, both the gross and fine-motor movements are quantitatively assessed. This removes the necessity for subjective assessment of performance common to a number of battery tests such as the MABC-2 or the BOT-2. Critically, the measurement of gross and fine-motor movement is synchronous, unlike with pen-on-paper tests where gross or fine movements have to be observed in isolation. The ability to investigate the link between fine and gross-motor performance on a task level represents an additional paradigm on which to investigate motor development and this is explored in chapters 2 and 4.

Given the important relationships between head rotation, hand movements and postural adjustment, it seems surprising that no research has examined how these systems become coordinated during normal and abnormal childhood development. The lack of extant studies into this topic seems to be due to the significant technical difficulties involved in measuring these movements simultaneously in adults, let alone children. Nevertheless, the recent advent of lower cost consumer electronics means that it is now feasible to start exploring the topic of the relationship between head, hand and posture. A system was developed which was capable of concurrently recording such data and conducted a small scale study to determine the feasibility of using this system to provide insights into children’s motor development. Chapter 2 introduces a portable system which is capable measuring performance in three key areas, at the extremity (task performance), at the head and at the CoP.

Maintenance of postural stability in conjunction with a concurrent cognitively demanding task (e.g. a skilled fine-motor behaviour) is often conceptualised as an attentionally demanding ‘dual-task’ (Huang and Mercer, 2001; Remaud et al., 2012; Van Impe et al., 2012; Weeks et al., 2003). These studies consistently report that postural stability worsens as a function of the attentional demands of the concurrent cognitive/fine-motor task, implying that the Central Nervous System (CNS) has limited resources at its disposal which it must distribute appropriately between the competing task demands (i.e. maintaining balance and performing the focal cognitive/fine-motor task). Others (Haddad et al, 2010), however, present contradictory findings which suggest that in young adults, instead of posture competing with fine-motor control the two systems actually work in concert: postural stability increasing as participants are asked to perform more demanding fine-motor control task (posting an object through an aperture of decreasing size). Regardless of the specific dynamic of this interplay, it is apparent that when an individual performs a fine-motor task their success is in part contingent on how well they can also maintain concurrent postural stability. It follows also that one might expect children and the elderly to be particularly challenged in performing such motoric ‘dual-tasks’ because it is understood that postural stability is particularly attentionally demanding, effortful and less of automated in these age groups (Haddad et al., 2012; Yogev-Seligmann et al., 2008).

A simple solution often employed, which reduces and mitigates concurrent postural demands whilst performing a fine-motor task, is to simply sit down. Sitting down on a chair provides postural support, resulting in a reduction in the demands placed on the nervous system (Berrigan et al., 2006; Forssberg and Hirschfeld, 1994). Now the system can devote more of its resources to the development of manual control ability. This is evidenced in studies indicating that the addition of postural support increases movement efficiency, with this effect being most pronounced in younger children (Saavedra et al., 2007; Smith-Zuzovsky and Exner, 2004). For example, reach-to-grasp movements reach adult-like manual control in children earlier in development when seated (Schneiberg et al., 2002).

However, the impact of seating on postural control whilst performing volitional arm movements, particularly in children, is unclear. To what extent does sitting modulate the disturbances in stability caused by arm movements and facilitate postural control? This is an important empirical question that needs to be addressed, as the majority of fundamental educational skills (e.g. handwriting) in childhood are acquired whilst seated at a desk. Is it enough for a child to adopt a seated posture in order to ameliorate the influence their postural stability has on their manual-control? It is conceivable that seating oneself may reduce postural demands to such a level that a participant’s cognitive/attentional resources are free to focus entirely on their fine-motor control (i.e. the task becomes no longer ‘dual’). Alternatively, even whilst seated a child’s postural stability may still influence with their fine-motor control in a dynamic fashion.

As discussed above, the development of manual control proficiency is intimately tied with postural stability (Bertenthal and Von Hofsten, 1998; Rochat, 1992; Thelen and Spencer, 1998). However, there are large differences in children’s ability to stabilise their CoM over the course of development (Kirshenbaum et al., 2001; Schmid et al., 2005; Shumway-Cook and Woollacott, 1985). The acquisition of postural control, from a frequently falling infant to an adult able to maintain stable posture over prolonged periods of time, is a well-documented developmental process (Hatzitaki et al., 2002; Hayes, 1982). This aptitude in postural control has direct consequences on manual action proficiency. As younger children are more challenged in postural control (as a function of their development), this directly impacts on their ability to execute fine-motor control tasks (Smith-Zuzovsky and Exner, 2004). Thus the impact of seating as provider of a stable platform from which fine-motor control tasks can be executed may vary with age. Chapter 4 examines postural stability in children at different stages in the developmental trajectory in order to address this issue. By comparing postural performance across different age groups, it is possible to gain insight into the development of seated posture, and to what extent seating differentially impacts postural stability across the developmental age range.

The efficiency of the postural system is measured not by its ability to stabilise itself during quiet stance, but on the extent that it stabilises the body during the execution of supra-postural tasks (Balasubramaniam et al., 2000; Riley et al., 1999; Stoffregen and Pagulayan, 2000). Whilst all arm movements used to perform manual control tasks perturb postural stability to some degree, not all movements are equal. Postural control provides a stable platform required for the successful execution of a particular task (Aruin and Latash, 1996; McNevin and Wulf, 2002; Stoffregen et al., 2006; Stoffregen et al., 2007). For example, increased task accuracy demands, such as slow, precise movements, result in the consolidation of degrees of freedom in the postural chain in younger children yielding an improvement in manual control performance (Haddad et al., 2012; Haddad et al., 2008). In contrast, dynamic or ballistic tasks, such as those experienced in aiming and reaching movements, pose a greater threat to postural stability, as they are more likely to perturb the body’s CoM. In situations where the suprapostural task follows a stable or predictable pattern, children should be able to compensate for expected displacement of the CoM produced by the arm movements. As such, predictable movements should have little impact on postural stability. Chapter 4 empirically tests these hypotheses, to investigate the interaction between different arm movements and stability whilst seated. Specifically, performance is compared in postural stability across a continuous, predictable tracking task, a ballistic and a precision tracing task.

A link between gross and fine-motor control?

In childhood, the development of fine and gross-motor proficiency generally proceeds in a predictable fashion as it increases with age. It is often assumed that the systems responsible for these processes are tightly linked and thus, highly correlated. Indeed, from an early stage in development, there is a clear relationship between postural control and completion of suprapostural tasks (De Graaf-Peters et al., 2007; Hopkins and Rönnqvist, 2002; Rochat, 1992; Thelen and Spencer, 1998; Wang et al., 2011). Increasing postural control impacts on one’s ability to generate fine-motor movements (Davids et al., 2000; Saavedra et al., 2007). In infancy, skilled postural control is a prerequisite for the acquisition of optimal distal reaching and grasping behaviours (De Graaf-Peters et al., 2007). The primary goal of the human postural system may be to provide stability, so that stable visual information can be used to guide skilful interactions with the world. Thus, it is assumed that stable posture forms the foundation upon which our earliest interactions with the environment are based (Fallang et al., 2005; Hopkins and Rönnqvist, 2002; Rochat, 1992; Thelen and Spencer, 1998).

A number of studies conducted with infants indicate a dependent relationship between fine and postural motor control. For example, the co-ordination of head movement with control of arm and hand has shown to be critical for successful reaching and grasping behaviour (Thelen and Spencer, 1998). Indeed, prior to the development of adequate head and trunk control, infants are able to perform aiming movements towards objects when provided with postural support (Amiel-Tison and Grenier, 1983; De Graaf-Peters et al., 2007; von Hofsten, 1982). As such, postural control may be seen as a control parameter for the development of fine-motor control/skilled manual dexterity.

The role of posture in the function of fine-motor control and its development may best be understood in the context of Anticipatory Postural Adjustments (APAs).

APAs are defined as those movements that arise from the activation of postural muscles before a voluntary movement, in anticipation of the destabilizing forces caused by the action of the movement itself. Consider an imminent volitional movement of the hand to catch a ball. The skilled postural system generates a pre-emptive momentum from displacement of the CoM, opposed in direction and magnitude to the momentum generated by the forthcoming hand movement. This APA results in a cancellation of the force generated by the movement and minimises the CoM displacement (Aruin and Latash, 1996; Girolami et al., 2010; Inglin and Woollacott, 1988; Patla et al., 2002). As an individual moves towards adulthood, the integration of postural and fine-motor control synergy through APAs becomes more proficient and allows for the development of increasingly more complex and skilled manual control behaviours (Schmitz et al., 1999).

Despite a clear rationale for the relationship between postural stability and fine-motor control, studies explicitly investigating this relationship have produced mixed findings. Case-Smith et al. (1989) took measurements on the posture and fine-motor assessment of infants scale for a sample of 60 children aged between 2 and 6. Scores on posture accounted for 12% of the variance in fine-motor control scores. More recently, Rosenblum and Josman (2003) investigated fine-motor performance using a standard peg-in-hole task and a postural sub-test from the BOTMP (Bruininks, 1978) in 47 five-year-old children. The results obtained were inconclusive, with data indicating a weak *negative* relationship between postural stability and fine-motor performance. Others have also reported weak relationships between gross and fine-motor functioning (Loria, 1980; Wilson and Trombly, 1984). The lack of a robust relationship between gross and fine-motor control reported in these studies points towards an alternative view; that these systems are disparate processes and functionally independent. There are a number of supporting arguments for this view. First, in the development of fine-motor control the progression from novice to skilled behaviour is both discontinuous and nonlinear

(Darrah et al., 2009; Hay, 1978; Kuhtz-Buschbeck et al., 1998) characteristic of emergent behaviour generated from a series of interconnected processes. Similarly, the development of efficient and skilful postural is a protracted process and does not follow a smooth linear progression between infancy and childhood to adulthood but is characterised by discontinuous development of postural stability over development (Kirshenbaum et al., 2001; Riach and Starkes, 1994; Schmid et al., 2005; Shumway-Cook and Woollacott, 1985). If postural control and fine-motor control are considered as two dynamical processes whose developmental trajectories are nonlinear, then one would predict the existence of a weak association between the two processes.

Examining the relationship between gross and fine-motor control is an important step in understanding developmental processes in childhood. Indeed, it could play a key role in understanding how manual dexterity might be influenced by posture. As such, this research question has potential implications for the way in which motoric difficulties are understood. If there exists a reliable relationship between gross and fine-motor control aptitude, it may possible to probe posture as a function of visuomotor task competency (e.g. handwriting).

However, the existing literature suggests that any relationship between the two is likely to be subtle. Subjective and summary measures of gross and fine-motor performance may be limited in their ability to detect the association between motor domains. For example, the MABC (Henderson et al., 1992; Henderson et al., 2007), BOTMP and BOT-2 (Bruininks, 1978; Bruininks and Bruininks, 2005) movement batteries and task-completion measures of performance such as catching (Davids et al., 2000) provide only rudimentary detail of task performance and are not well suited to probing an association between gross and fine-motor ability.

Furthermore, the current literature has focussed on acute clinical populations or small numbers (n < 100) from a normal population sample. Any underlying relationship may be obscured due to methodological difficulties and practical limitations of administrating tests of gross and fine-motor control to large populations. Chapter 5 uses the low-cost equipment to begin to address the issue of how to collect accurate postural data outside of the laboratory environment. Using this equipment it is possible to investigate developmental association between fine and gross-motor ability.

The structure of this thesis

The main aim of this thesis was to develop a platform which was capable of sensitively measuring the postural and fine motor control of large numbers of children with the sole aim of understanding the link between the developments of the two systems.

In order to achieve this the main objectives were to develop a sensitive, repeatable and assessment battery suitable for all age groups which could be deployed in large numbers.

The aim of the first chapter was to address the limitations observed in fine motor control. Understanding the link between two discrete systems such as postural control and fine motor control necessitates detailed investigation of both. Chapter 1 introduces methodological and statistical techniques sensitive to what are predicted to be extremely subtle effect of age and gender on tasks requiring a similar skillset to those observed in school-related tasks. A platform,

In chapter 2, measures of fine motor control described in chapter one are complemented with a postural measure. This chapter therefore starts to develop techniques capable of probing the link between the control of posture (more specifically the control of head movement and centre of gravity movement) and the performance on a fine motor task. The development of equipment capable of synchronous data capture at the head, centre of pressure and hand represents a platform on which to base large-scale measurements by taking the measurements out of the laboratory environment and into the region of interest, namely the classroom.

Chapter 3 develops the equipment used in chapter 2 by addressing the factors which limit the scalability of the test platform, namely the use of the Xsens device. This chapter details the development of the optical motion capture system and compares its output to that of the clinical-grade measurement equipment in the measurement of posture development. One of the main aims of this chapter is to highlight the limitations of using off-the-shelf equipment for measurement, particularly in the measurement of postural development in children, where there are possible confounding effects of mass variability between populations.

While chapter 3 introduced the development of a postural measurement system sensitive to the effects of age on postural sway, there are specific limitations of the application of this equipment to postural sway. In chapter 4, the capability of the optical system was such that tracking of up to three markers was possible. This resulted in a system which was capable of determining head movement in translation and rotation and extended its capability for analysing head movement in response to specific tasks.

Finally, chapter 5 introduces a system which represents a fully scale postural measure. This was used to compare postural stability and fine motor control as independent processes. The standardised motor battery developed in chapter 1 was assessed against the postural measures obtained from the optical motion capture system developed in chapters 3 and 4. The aim here was to demonstrate that the equipment could be used on a large scale and operated independently of specialist support, thus demonstrating the utility of the optical motion capture system as a device capable of being used in the classroom and, on that point alone, a viable alternative to paper-based assessments of postural stability.

Chapter 1: Manual control sex differences in 4 to 11 year old children

Overview

The question of how fine motor control develops as a function of age is not well understood, and is likely due to limitations in pen-on-paper assessments of fine motor performance. This chapter introduces a computerised test battery which can be applied to large numbers of school-age children in order to assess fine motor control development as a function of age and gender. This study represents the fine motor performance assessment component of the fine and gross (postural) investigation undertaken in this thesis, with the platform described in this chapter being developed to incorporate postural assessment in subsequent sections of the thesis.

1.1 Introduction

Large population-based studies of children reliably find sex differences for specific aspects of cognitive function (Strand et al., 2006; Gur et al., 2012). Girls outperform boys on standardised tests of attention; emotion recognition; verbal and facial memory. Boys outperform girls on sensorimotor, visuo-spatial and mathematical problem-solving tasks. These findings complement neuro-imaging research that finds structural differences in the developmental trajectories of the male and female brain (Lenroot et al., 2007) and a clinical literature which indicates an increased prevalence of certain neuro-developmental disorders in males (Rivet and Matson, 2011). Nonetheless, evidence from meta-analyses (Hyde, 2005) suggests that importance of these sex differences is often overstated. Hyde (2005) argues in favour of a ‘gender similarities hypothesis’, pointing out that on-balance the sexes are similar in many more facets of their psychological functioning than dissimilar.

Sex differences in cognitive functioning are also often task-specific, small in magnitude and/or highly variable between individuals (Halpern et al., 2007), leading to warnings that they are of limited value as heuristics for explaining children's everyday behaviours (e.g. they are not amenable to explaining why an individual child is underperforming in the classroom). 'Media sensationalising' of relatively innocuous sex differences can have profoundly negative socio-cultural impacts (Eliot, 2011). For example, male advantages on visuo-spatial tasks are repeatedly pointed to as an overly simplistic and reductive excuse for the under-representation of females in mathematical and scientific professions (Hyde et al., 2008; Halpern et al., 2007).

From an educational perspective it is therefore important that we gain a clearer understanding of the degree to which sex impacts on childhood development, because this may lead to more effective teaching strategies (e.g. recognising significant differences or promoting inequality in specific curriculum areas). In particular, there is a paucity of objective empirical research to help in understand the role that sex may play in the development of children's manual motor skills. This is despite the topic being of fundamental educational importance because of the instrumental role that activities such as handwriting and drawing play in children's academic progress, as well as the critical function played by eye-hand coordination in basic activities of daily living (such as independent washing, dressing and feeding (Cools et al., 2009)).

Epidemiological studies have found that Developmental Coordination Disorder (DCD) is more common in boys than girls after evaluating evidence for sex differences in general motor-skill development (i.e. treating motor-skills as a homogenous category) and for gross-motor tasks (i.e. activities involving locomotion and movement of the torso (Malina, 2004)). Lingam et al. reported a ratio of about 2:1 (Lingam et al., 2010) whilst Kadesjö and Gillberg (1999) found a ratio of 4-7:1. If DCD is simply a characterisation of the motor skills of children at one end of a continuum, then sex differences in a clinical population might reflect differences of development in a typical population. Contradicting this notion, Malina, Bouchard and Barr-Or (2004) report that sex differences in the rate of acquisition of recognised motor-milestones during infancy are few, inconsistent and possibly culturally determined. Once adolescence is reached, sex-differences in gross-motor skills are well established, with good evidence of males showing better performance on large-object control tasks, in particular tests of throwing and striking ability (Malina, 2004; Lorson and Goodway, 2008; Junaid and Fellowes, 2006; Butterfield et al., 2012; Barnett et al., 2010; Raudsepp and Paasuke, 1995) with a meta-analysis (n = 31,444) indicating that the performance gaps for these sorts of tasks widen with age (Thomas and French, 1985). However, post-pubescent individual sex differences in basic anatomy (e.g. relatively greater increases in muscle tissue in males) are the primary driver behind these emerging male advantages (Thomas and French, 1985). Thus collectively these findings do little to enlighten our understanding of how sex affects fine-motor manual control development, particularly in the period between infancy and pre-pubescence in typically developing children.

Children’s fine-motor skills (i.e. activities distinguished though their requirement for a high-degree of precision and typically involving some form of manual object manipulation (Malina, 2004)) are more readily associated with academic performance than gross-motor skills, while also being less dependent on muscular strength. For example, it is acknowledged that the difficulties with handwriting experienced by most children with DCD are probably the primary explanatory factor behind the poor academic achievement associated with this condition (Blank et al., 2012). Unfortunately, there is a lack of well controlled studies of sex differences in fine-motor control, with the existing research literature often presenting conflicting results.

Gur et al. (2012) have reported that males are faster in basic speeded manual responses (n = 3,500 youths from 8 to 21 years old), but these advantages do not emerge until adolescence and the tests of motor ability they used were relatively simplistic, requiring participants to tap as fast as possible on a spacebar and move a mouse to click on a square that appeared at unpredictable on-screen locations. The results do agree, however, with a smaller (n = 106, 9 to 17 year olds) cross-sectional study that found a male advantage for learning manual sequences (finger-tapping sequences (Dorfberger et al., 2009)). In contrast, Poole et al. (2005) reported that girls were quicker in a task which required participants to insert and remove pegs from a wooden board as quickly as possible, using their preferred and then non-preferred hand (n = 406 from 4-19 year olds). Two studies (Hellinckx et al., 2013; Junaid and Fellowes, 2006) have reported that between the ages of 7 and 12 years older girls outperform boys on a standardised pen-and-paper battery of manual dexterity tasks (from the original version of the Movement ABC assessment battery (Henderson et al., 1992)). Sex differences were also observed on pen-and-paper handwriting tasks examined during one of these studies (Hellinckx et al., 2013) (a female advantage for quality but not speed of writing was found in a sample (n = 131) of 7-12 year olds). Once more, these results conflict with a comparable study (n = 127) that reported no sex differences in 5-12 year-olds on a similar pen-and-paper drawing task (Albert et al., 2010).

The difficulty with previous investigations of fine-motor control is that they often have employed assessments that rely on subjective scoring techniques, have poorly defined outcome measures and/or inherent confounds generated by the use of multiple task strategies (Culmer et al., 2009), for example adolescent boys could perceivably be strongly motivated to performed a speeded task quickly. Moreover, the emphasis on speeded responses in some studies is problematic, because anatomical differences between genders rather than differences in central control mechanisms might explain performance differences. Thus the majority of current studies are unsatisfactory because they assess fine-motor control with respect to speed of the movement, while not considering the other factors that could in broad terms describe a movement's 'quality', such as how smooth or accurate the movement was (Poole et al., 2005; Gur et al., 2012). Another limitation of extant studies is the reliance on subjective assessments on qualitative aspects of movement (Hellinckx et al., 2013; Albert et al., 2010).

A technologically innovative approach to investigating sex differences in fine-motor manual control which provides more objective measures involves the utilisation of digital tablets to record participants' movements (Culmer et al., 2009; Dorfberger et al., 2009; Rueckriegel et al., 2008; van Mier, 2006; Blank et al., 2000; Genna and Accardo, 2012). This methodology typically involves participants using a stylus to interact with the tablet (like using a pen with paper) which means this approach likely has greater ecological validity for investigating the aspects of manual control that are important for handwriting development. Studies using this technology (not always to explicitly address the issue of sex differences) also report conflicting results. Dorfberger et al. (2009) reported that girls were significantly faster at writing nonsense words in early blocks of trials (n = 116, 9-17 years age range) but this effect disappeared in later blocks, before a male advantage appeared in the final blocks for the oldest age group (17 years). Rueckreigel et al. (2008) reported that males were faster in a drawing task (producing a circle) but not on a sentence or repetitive letter writing task (n = 187, 6-18 years old), though the study did not stratify the sample for age. Van Mier (2006) found no sex differences in a task that required children to move a handheld stylus around small and large targets on a screen (n = 60, 4-12 years age range). Blank et al. (2000) also found no sex differences on a task requiring the repetitive drawing of straight lines and circles (n = 53, 7-14 years age range). Genna & Accardo (2012) found a small female motor advantage in younger age-groups when carrying out five cursive handwriting tasks (n = 208, 7-14 years age range). There are difficulties with interpreting these results, however, because the age ranges frequently include pre- and post-pubescent children and some of these tasks have a degree of familiarity and cultural dependence (i.e. some require prior knowledge of letters, words, grammar). It is clear that the issue of pre-pubescent sex differences in fine-motor manual control has yet to be adequately investigated. In order to address this issue, a system capable of providing detailed kinematic information regarding how children interact with visual stimuli presented on a tablet PC screen was used. Performance in children aged 4-11 years was investigated, as this age range can be considered pre-pubescent with reasonable confidence. Moreover, this age range corresponds to ‘primary schools’ within the UK educational system - schools where the focus is on the development of core skills including handwriting. As demonstrated by the variety of assessment methods used in the previous research, fine-motor ability can be investigated via an incredibly wide range of skills (e.g. manual response reaction time tasks, manual sequence learning, writing and drawing tasks).

Nevertheless, a common feature of many of these canonical ‘fine-motor’ tasks is that they require precise ‘hand-eye coordination’. Such visuomanual control is often discussed as being particularly important in manual tasks requiring object manipulation (Gowen and Miall, 2006; Johansson et al., 2001; Pelz et al., 2001; Huang and Hwang, 2012). Combining this consideration with the fact tablet methodology lends itself to presenting tasks that involve in-hand manipulation of a stylus; this chapter focussed on testing basic visuo-manual control skills that are likely to underpin a child’s proficiency for controlling a stylus. Therefore, three novel tasks requiring the control of a handheld stylus were created. Each task tapped into slightly different control mechanisms: tracking moving targets, tracing shapes and making aiming movements. These tasks tap into specific control mechanisms (tracking relies on the ability to predict target movement, tracing shapes requires precise force control, whilst aiming movements rely on accurate feed-forward mechanisms and fast implementation of online corrections). Testing a large number of children on this task battery would allow solid conclusions to be drawn regarding the degree to which sex influences the development of ‘manual control’ within pre-pubescent children.

On the basis of the ‘gender similarities hypothesis’ (Hyde, 2005), a small but significant difference in manual control between the sexes was predicted. Furthermore, given evidence of gross-motor sex differences increasing with age during adolescence (Thomas and French, 1985), it is probable that an age-related improvement in manual-control, during pre-pubescence might be found - improvements that were moderated by sex.

1.2 Methods

1.2.1 Participants

Participants were recruited from two primary schools in West Yorkshire, UK. A total of 422 out of 484 students agreed to participate (the others were either absent on the day of testing or did not give consent). Table 1 provides descriptive statistics for the age, sex, handedness and distribution across categorical age bands. The University of Leeds Ethics and Research committee approved this study and it was performed in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki.

Table 1. Descriptive statistics for age, sex and handedness of whole sample and across age-bands

Variables	Total Sample	4 to 5 year olds	6 to 7 year olds	8 to 9 year olds	10 to 11 year olds
n	422	80	122	143	77
Sex[1]					
Male	216 (51%)	40 (50%)	60 (49%)	80 (56%)	36 (47%)
Female	206 (49%)	40 (50%)	62 (51%)	63 (44%)	41 (53%)
Handedness[1]					
Right	369 (87%)	71 (89%)	111 (91%)	123 (86%)	64 (83%)
Left	53 (13%)	9 (11%)	11 (9%)	20 (14%)	13 (17%)
Age (years, months)					
Median	8,1	5,4	7,2	9,1	10,7
IQR	6,6 to 9,8	4,10 to 5,9	6,7 to 7,6	8,7 to 9,7	10,4 to 11,0
Range	4,6 to 11,5	4,6 to 5,11	6,0 to 8,0	8,0 to 10,0	10,0 to 11,5

[1] Denominators for percentages are relative to each column’s n (see first row of the table)

1.2.2 Materials

The test battery was designed and presented using the Clinical Kinematic Assessment Tool (CKAT), a custom software package specialised for presenting interactive visual stimuli on a tablet laptop computer screen while simultaneously recording participant’s kinematic responses to these stimuli via interactions with the screen using a handheld stylus (see Culmer, Levesley, Mon-Williams and Williams (2009) for a description of the underlying architecture). CKAT was implemented on Toshiba tablet portable computers (Portege M700-13P, screen size: 303x190mm, 1280 x 800 pixels, 32 bit colour, 60 Hz refresh rate) with a pen-shaped stylus (140mm long, 9mm diameter) used as an input device. For every trial within every subtest, the position of the stylus was recorded at a rate of 120 Hz, with a 10Hz dual-pass Butterworth filter applied to the raw positional data at the end of each testing session. The CKAT software calculated a range of spatial, temporal and frequency-based kinematic metrics that described a participant’s movements in detail (see Culmer et al. (2009)).

1.2.3 Procedure

Participants were seated at a table of appropriate height for their age. A tablet computer in landscape orientation was placed in front of them with its screen folded flat. The edge of the tablet nearest the participant was 15 cm from the table’s edge. The ‘testing stations’ were placed around the periphery of a large classroom, with one researcher sat to the side of each station. This arrangement allowed for groups of participants to be tested simultaneously. To minimise distractions during testing, stations were separated by at least 2 metres, participants faced away from one another and direct sources of light were removed to minimise reflection on the tablet screen. For each participant, the battery was completed in a single session lasting approximately 12-15 minutes. The test battery comprised of three subtests, presented to all participants in the following fixed order:

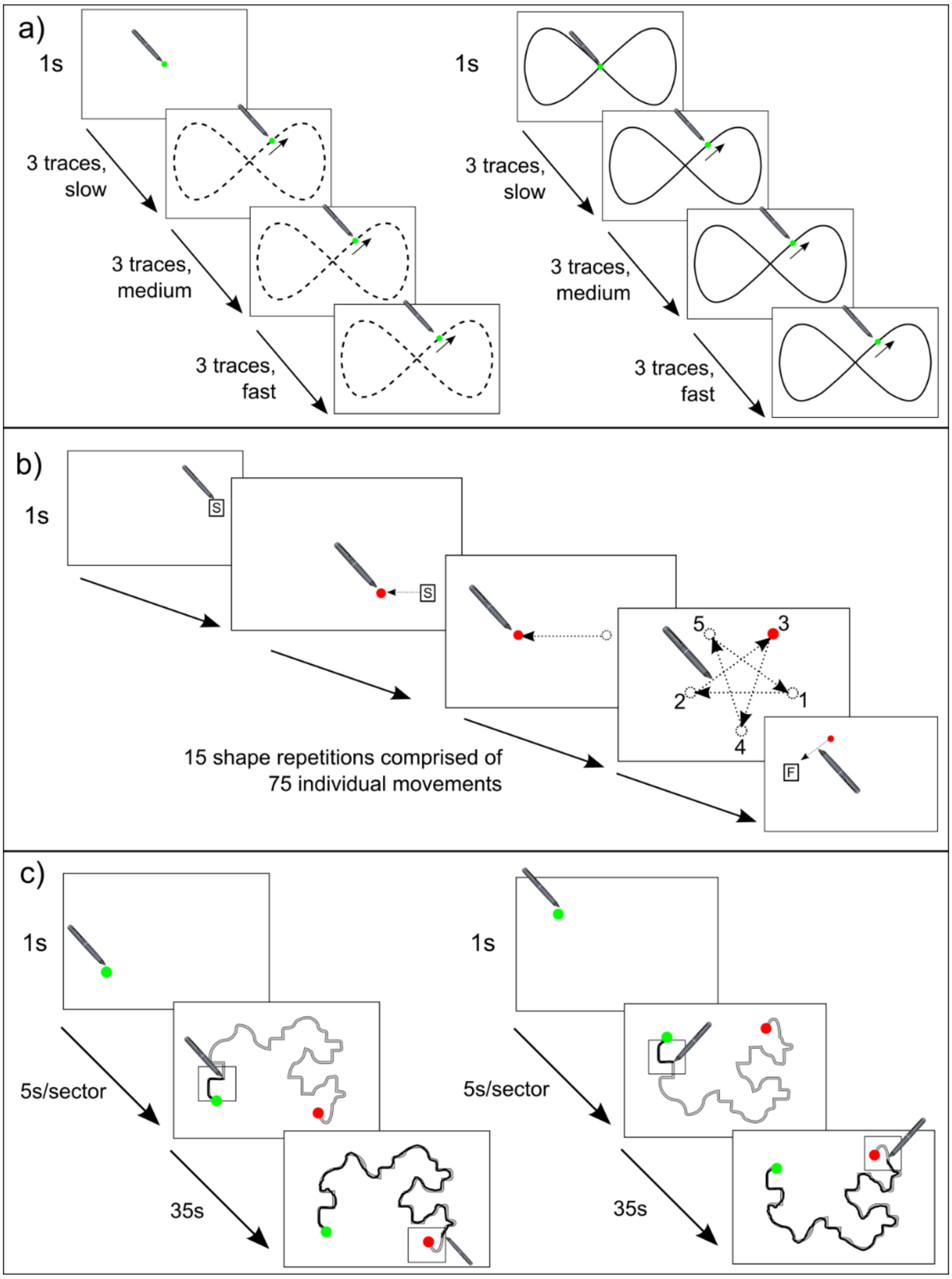


Figure 1. Illustrations of the three manual control battery tasks: Tracking, Aiming and Tracing

(a) Left is a schematic of first tracking trial (i.e. without guide-line), annotated with a dotted line to indicate the trajectory of the moving dot. Right is a schematic of the second tracking trial, which included the additional guide-line. (b) Schematic of the aiming subtest, annotated with dotted arrows implying the movements participants would make with their stylus to move off the start position, between target locations and to reach the finish position. On the 4th panel further annotations indicate the locations in which targets sequentially appeared, with numbers indicating the sequence in which they were cued. (c) Left is a schematic depicting tracing path A and right is a schematic depicting tracing path B. The black shaky lines are an example of the 'ink trails' a participant would produce with their stylus in the course of tracing.

1.2.3.1 Description of the test battery

1.2.3.1.1 Tracking

This sub-test comprised of two trials. In the first, participants began by placing the stylus tip on a static dot (10mm diameter) presented in the centre of the tablet's screen. After a second's delay the dot moved across the screen and participants were instructed to keep the tip of the stylus as close as possible to the dot's centre for the remainder of the trial. The motion was described by two oscillating sinusoidal waveforms in the axes of the screen. The frequencies and amplitudes of these waveforms were in a 2:1 ratio, resulting in a repeating 'figure of eight' spatial pattern (see Figure 1) with height = 55mm and width = 110mm. The trial required participants to track the moving dot (10mm diameter) for 84 seconds through a total of nine 'figure of eight' revolutions comprising a 'slow' pace for the first three revolutions, transitioning to a 'medium' pace on the fourth revolution before transitioning to a 'fast' pace for the final three revolutions (i.e. a trio of revolutions at each successive speed). The frequencies specified for the waveforms in order to produce the three speeds and the resultant velocities of the dot are reported in Table 2.

Table 2. Stimulus frequency parameters for the three tracking task speeds, plus resultant velocities and subtest duration

Speed	X-axis Frequency (Hz)	Y-axis Frequency (Hz)	Time per Figure of eight (sec)	Average Resultant Velocity (mm/s)	Minimum resultant Velocity (mm/s)	Maximum Resultant Velocity (mm/s)
Slow	0.125	0.0628	16	41.9	28.6	61.1
Medium	0.25	0.125	8	83.8	57.2	122.2
Fast	0.5	0.25	4	167.7	114.3	244.3

The second tracking trial was identical to the first but the spatial path followed by the dot was provided in the background of the screen as a black 3mm wide guide-line. This guide was expected to aid participants by providing additional information about the dot's path. See Figure 1a for illustrations of both trials. Root Mean Square Error (RMSe), a measure of the spatio-temporal accuracy of participant's tracking, provided an index of performance on the tracking task. RMSe was calculated as the straight-line distance in millimetres between the centre of the moving target and the tip of the stylus for each sampled point during the time-series. For each tracking trial (i.e. without and with guide-line) a mean value for RMSe with respect to each speed condition (i.e. a slow, medium and fast measure per trial) was calculated and statistically analysed.

1.2.3.1.2 Aiming

The aiming subtest required 75 successive aiming movements to target-dots on the tablet's screen. Participants started by placing their stylus on the start position (a circle with the letter 'S' within it), triggering a target-dot (5mm diameter) to appear at the location 1 (see Figure 1b). Participants were instructed to respond as quickly and accurately as possible to this presentation by sliding their stylus across the screen to hit the dot. Arrival resulted in the dot disappearing and a new target-dot simultaneously appearing at location 2. Participants had to respond to this second target in the same manner as the first, in turn causing it to disappear and the next target-dot to appear at location 3. Participants repeated this pattern of response until the 75th target, after which the finish position (a circle with the letter 'F' within it) appeared on screen (see Figure 1b). The overall sequence of 75 target-dot presentations encompassed two experimental conditions. The Baseline condition constituted the first 50 target-dot presentations. Within it target-dots cuing to each of the 5 numbered target locations were presented in order before location 1 was re-cued again and the 5-step sequence repeated, ten times consecutively in the course of this condition (i.e. participants' resultant movements approximated drawing the star shape outlined in fourth panel of Figure 1b ten times in a row). Distance from one target location to the next was a constant 113mm. The remaining 25 targets constituted the Online Correction condition, within which six ‘Jump’ events pseudo-randomly programmed. On these movements, the target-dot instantaneously disappeared when the participant was within 40mm of the intended target whilst another appeared simultaneously at the next-to-be-cued location in the established sequence. This required an online correction to their initial aimed movement. Participants were not told about the existence of Jump events. Movement Time (MT) was calculated for each of the 75 discrete aiming movements and defined as the time it took for participants to leaving one target location and arrive at the next, in seconds. MT was calculated with respect to the final target position (i.e. after the dot had jumped) for Jump events. Fast MTs were indicative of an optimal task response. For statistical analysis, a median value for the MT of aiming movement made during Baseline experimental conditions was calculated. This was compared to two further median MT values derived from responses during the Online Correction condition. Within this condition a median MT value was calculated for the six aimed movements made in response to the ‘Jump’ events and a separate median was calculated for responses made to the interspersed normal stimuli presentations (termed the ‘Embedded-Baseline’).

1.2.3.1.3 Tracing

The tracing subtest comprised six trials in total. In each trial the participant was required to place their stylus on the start position on an otherwise blank screen. After one second a tracing path (4mm width) would appear, adjoining the start position to a finish position marked at the other end of the path (see Figure 1c). To complete the trial, participants had to move the stylus along the tracing path to the finish position; trying as best they could to stay within the path’s guide-lines whilst doing this. The stylus produced an on-screen ‘ink trail’ (like a real pen), providing feedback to participants on their progress. Each trial presented one of two paths (A or B), which had identical geometry but were mirrored vertically (see Figure 1c). The paths were presented in alternate trials (path A on odd-numbered trials and path B on even), with each traced three times in total in the course of the subtest. In each trial, a black transparent box was presented on the screen next to the start position encompassing approximately one seventh of the length of the tracing path. At 5 second intervals, after the participant had begun tracing, this box shifted sequentially along the path, until after seven shifts (totalling 35 seconds) it arrived next to the finish position. Participants were explicitly instructed to try to remain within this box with their stylus whilst they were tracing along the path. The addition of this 'pacing' box was intended to standardise the speed (approximately), preventing variation in individual participants' prioritisation of 'speed' and 'accuracy' with respect to their performance from confounding results. Path Accuracy (PA) for each trial was defined as the arithmetic mean (in mm) across all samples within each trial for the distance from the stylus to an idealised reference path (i.e. path A or B). Initial exploration of the data suggested that there was a degree of individual variation in the Movement Time (MT) within each of the tracing trials (see Table 3).

Table 3. Descriptive statistics for Movement Time (MT) during tracing trials

Trial Number	**Movement Time (in seconds)**				
	Median	IQR	Range	n ± 5sec [1]	% n ± 5sec[1]
1	38.3	36.4 to 41.4	26.8 to 93.9	119	28%
2	37.2	35.6 to 40.1	2.7 to 82.6	106	25%
3	37.4	35.4 to 39.8	20.3 to 72.3	104	25%
4	37.1	35.3 to 39.7	1.6 to 69.6	91	22%
5	37.1	35.3 to 39.4	2.8 to 70.1	102	24%
6	36.9	35.1 to 39.8	16.7 to 60.9	112	27%

[1] Participants whose MT was either >41 seconds or <31 seconds (i.e. more than 5 seconds [i.e. 1 'pace box' or more] adrift either side of the expected completion time)

A composite metric was therefore created that adjusted participants' PA score to take account of their temporal accuracy. 36 seconds was set as the optimum MT, with each trial’s PA score inflated by the percentage deviation from this time. This gave a new unitless measure combining estimates of spatial and temporal accuracy, called the penalised Path Accuracy (pPA) score. A median pPA value for participant’s performance on the three tracing trials presenting Path A and a separate one for the trials presenting Path B were calculated and analysed statistically (attempted statistical modelling of pPA as a repeated measure with an individual value for each of the six separate trails resulted in a model which failed to converge, hence separate summaries for A and B were instead analysed).

1.3 Results

All analyses were conducted in R (version 2.15.1, R Development Core Team, 2012). Primary outcomes for each subtest (RMSe, MT and pPA) were initially explored using graphs, skew and kurtosis values and Shapiro-Wilks tests of normality. Prior to statistical analysis reciprocal transformations were applied to all three outcome variables to normalise their distributions and resolve outliers. Performance on each of the transformed outcomes was then analysed separately using Multi-level Linear Modelling (MLM) techniques (approximately equivalent to using mixed Generalised Linear Models); see Field (2012) for a discussion of the advantages of MLM. All MLMs used a maximum likelihood method to estimate the model and specified age band (4-5, 6-7, 8-9 and 10-11 years) and sex (male or female) as between-subject independent variables. Within the MLM model used to analyse RMSe (the primary outcome measure for the tracking subtest) two additional repeated measures, both nested within participants, were also included to examine the influence of Trial Type (With- or Without-Guide) and Speed (Slow, Medium or Fast) respectively. Equivalently, for MLM analysis of MT (the primary outcome for aiming subtest) a repeated measure of response-type (i.e. Baseline, Embedded-Baseline or Jump Event) was included. Whilst modelling pPA, the outcome measure for tracing, a repeated measure of Path Type (i.e. tracing Path A or B) was included.

A standardised protocol for conducting MLM analysis was followed (Butterfield et al., 2012). First, a baseline model including no predictors except the intercept was generated. Next, a sequence of nested models was generated that added in, one at a time, the necessary pre-specified Main Effects and associated interaction terms until a final full factorial model was reached. The effect of each Main Effect/Interaction term was then judged using likelihood-ratio tests which compared: (1) fit for the model in which a Main Effect/Interaction was included for the first time against (2) the fit for the immediately preceding model in the nested sequence. Thus, each likelihood-ratio test evaluated whether addition of a specific term (Main Effect or Interaction) significantly increased the explanatory power of the model being built.

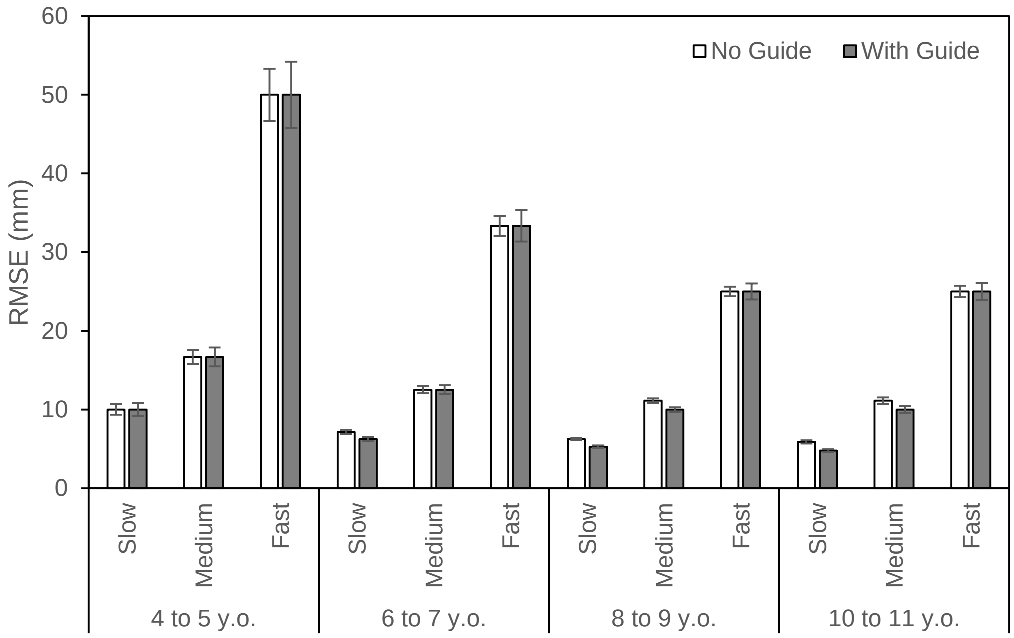


Figure 2. Bar-chart of Root Mean Square Error (RMSe) by Age-Group, Trail-Type and Speed.

RMSe (mm) is a measure of average spatial accuracy across time whilst manually tracking. Presentation of a guideline underneath the tracked target significantly improved performance on this outcome but this advantage was moderated by both age (larger benefit in older age groups) and speed (larger advantage at slower speeds), resulting in a statistically significant 3-way interaction between these factors (p < .001). There were no main effects or interactions involving sex on this outcome. Note: Error bars represent 95% confidence intervals.

1.3.1 Tracking

For two participants, a recording error on this subtest meant their response had to be excluded from this portion of the analyses (leaving n = 420). MLM analysis of the reciprocal RMSe outcome found that the following 3-way interaction was significant: Age Band X Speed X Trail Type, ($\chi^2(6) = 86.24$; p <.001), depicted in Figure 2. All main effects and two-way interactions which involved only these three factors were also significant ($p < .05$). Meanwhile, the 4-way interaction that also included sex was non-significant ($\chi^2(8) = 10.21$; $p = .251$). No 3- or 2-way interactions involving sex as a factor were significant (all $p > .05$). There were no main effects or interactions involving sex on this outcome. In relation to the significant 3-way interaction, Figure 2 suggests RMSe does not improve for the youngest age group when in the second trial the additional guide-line is provided, irrespective of the speed of the dot. For older age groups their RMSe improves on the guide-line trial (higher scores = better after the reciprocal transform), with this benefit increasing with age but also diminishing as the target moves faster. This interpretation is supported by Table 4, which presents estimated effect sizes for performing with and without the guide-line for each age group at each speed.

Table 4. Mean and Standard Deviation (SD) for Reciprocal Root Mean Square Error (RMSe) whilst tracking without and with a guide-line, with effect estimates sizes for between task differences

		Reciprocal RMSe (mm^{-1})				
		Without Guide-line		Without Guide-line		
Age Band	**Target Speed**	mean	SD	mean	SD	Cohen's d[1]
4 to 5 years	Slow	0.10	0.03	0.10	0.04	0.07
	Medium	0.06	0.02	0.06	0.02	0.09
	Fast	0.02	0.01	0.02	0.01	0.21
6 to 7 years	Slow	0.14	0.03	0.16	0.04	0.86
	Medium	0.08	0.02	0.08	0.02	0.32
	Fast	0.03	0.01	0.03	0.01	0.06
6 to 7 years	Slow	0.16	0.03	0.19	0.04	1.09
	Medium	0.09	0.01	0.10	0.02	0.81
	Fast	0.04	0.01	0.04	0.01	0.21
10 to 11 years	Slow	0.17	0.03	0.21	0.04	1.48
	Medium	0.09	0.02	0.10	0.02	0.88
	Fast	0.04	0.01	0.04	0.01	0.19

[1] Effect size for the mean difference between reciprocal RMSe with and without a guide-line

‘Large’ benefits were found for tracking with the guide-line in three eldest age bands when the target speed was slow, with these benefits increasing successively with age. Similarly, ‘moderate’, increasing to ‘large’ benefits with age also emerged in these age bands when the target moved at the medium speed. Effect sizes are interpreted using threshold's suggested by Cohen (1988) ('Small' $d = .20$; 'Moderate' $d = .50$; 'Large' $d > .80$).

1.3.2 Aiming

One participant had only partial data recorded for the Jump condition and therefore their responses were excluded from this portion of the analyses. For the remainder of the sample (n = 421), MLMs of the reciprocal MT outcome revealed a significant 3-way interaction (depicted in Figure 3) for: Age Band X Sex X Response Type, ($\chi^2(6) = 14.79$; $p = .022$). Subordinate main effects for Age Band and Response Type and 2-way interactions for Sex X Age Band and Age Band X Response Type were also significant (all $p < .05$). All remaining main effects and interactions were non-significant ($p > .05$). Figure 3 shows evidence of sex differences arising in MT during baseline and embedded-baseline trials but not during 'jump' events.

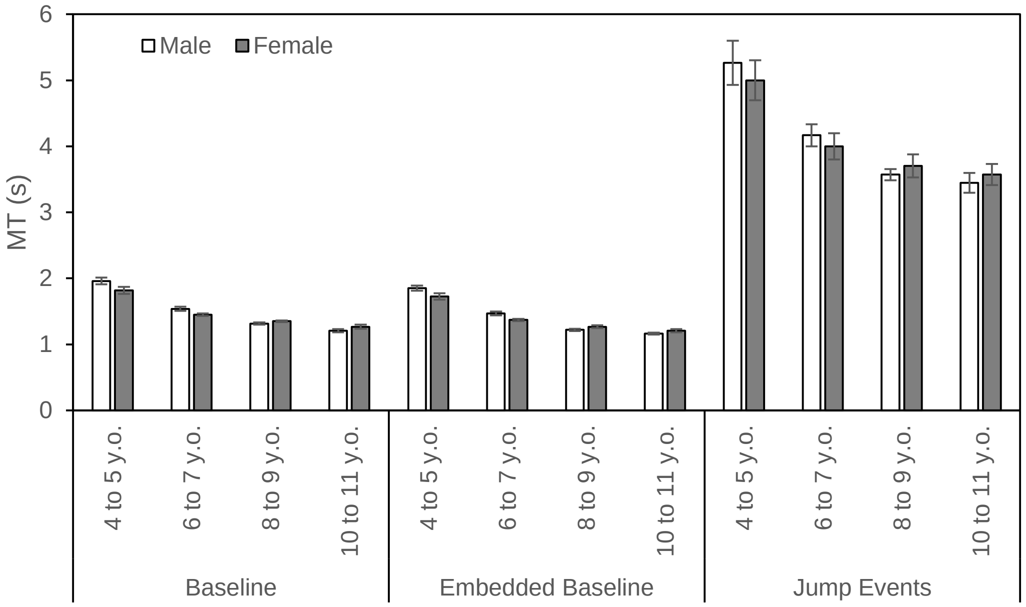


Figure 3. Line-graph of Movement Time (MT) by Age-Group, Sex and Experimental Condition.

MT (s) is a measure of average time to move from one target to the next in a serial aiming task. In normal Baseline and Embedded-Baseline trials female participants had a statistically significant advantage over males in the younger age-groups, with this crossing over in the older age groups (i.e. no sex differences or a male advantage dependent on age group and condition). Meanwhile, no significant differences between sexes were observed, irrespective of age, for 'Jump' aiming movements that required additional online corrections. This was reflected in statistical analysis finding a significant 3-way interactions between age group, sex and condition ($p < .05$). Note: Point estimates and associated 95% confidence intervals for each sex group within an age-group have been artificially moved on the horizontal axis so that they display side-by-side, preventing overlaps obscuring interpretation.

In both these conditions a similar pattern is shown: a consistent female advantage in the youngest two age groups (4-5 and 6-7 year olds) which shows signs of reversing with age. In the older two age groups (8-9 and 10-11 year olds) there was either no significant sex difference within age group or a significant male advantage. Table 5 investigates the magnitude of the sex differences observed within this interaction, presenting descriptive statistics for male and female performance within each age-band on each condition. The corresponding effect-size for these mean differences indicate none of the sex differences constitute greater than a 'Small' effect in terms of their magnitude (i.e. $0.2 < d < 0.5$).

Table 5. Mean and Standard Deviation (SD) for Reciprocal Movement Time (MT) whilst aiming by sex across age bands and experimental conditions, with effect size estimates for between sex differences

		Reciprocal MT (sec^{-1})				
		Males		Females		
Experimental Condition	**Age Band**	Mean	SD	mean	SD	Cohen's *d*[1]
Baseline	4 to 5 years	0.51	0.10	0.55	0.14	0.32
	6 to 7 years	0.65	0.09	0.69	0.11	0.39
	8 to 9 years	0.76	0.10	0.74	0.10	0.20
	10 to 11 years	0.83	0.12	0.79	0.12	0.33
Embed. Base.	4 to 5 years	0.54	0.11	0.58	0.13	0.33
	6 to 7 years	0.68	0.11	0.73	0.12	0.43
	8 to 9 years	0.82	0.12	0.79	0.11	0.26
	10 to 11 years	0.86	0.14	0.83	0.12	0.23
Jump Events	4 to 5 years	0.19	0.04	0.20	0.09	0.14
	6 to 7 years	0.24	0.03	0.25	0.04	0.28
	8 to 9 years	0.28	0.04	0.27	0.03	0.28
	10 to 11 years	0.29	0.04	0.28	0.04	0.25

[1] Effect size for the mean difference between sex for Reciprocal MT

1.3.3 Tracing

Multilevel linear modelling found significant main effects of both age band ($\chi^2(3)$ = 259.57; *p* < .001) and sex ($\chi^2(1)$ = 15.25; *p* < .001) upon reciprocal pPA but no additional significant main effect for Path type (A or B) or any significant 2- or 3-way interactions (all *p* > .05). Inferring from descriptive statistics, the main effect of sex indicated girls' mean reciprocal pPA score was significantly higher (better) than boys (girls: mean [SD] =0.86 [0.20]; boys: mean [SD] = 0.78 [0.21], *d* = 0 .37). Post-hoc tests also showed that from one age band to the next 6-7 year olds out-performed 4-5 year olds (mean difference [95% CI] = 0.15 [0.07 to 0.24]; *p* <.001, *d* = 1.09); 8-9 year olds were better than 6-7 year olds (mean difference [95% CI] = 0.16 [0.09 to 0.22]; *p* <.001, *d* = 0.68) and 10-11 year olds outperformed the 8-9 year olds (mean difference [95% CI] = 0.10 [0.02 to 0.18]; *p* = .007, *d* = .83). Effect sizes suggested ‘Moderate to Large-sized’ improvement with age but only a small to moderate sized effect for sex. See Figure 4 for an illustration of these effects.

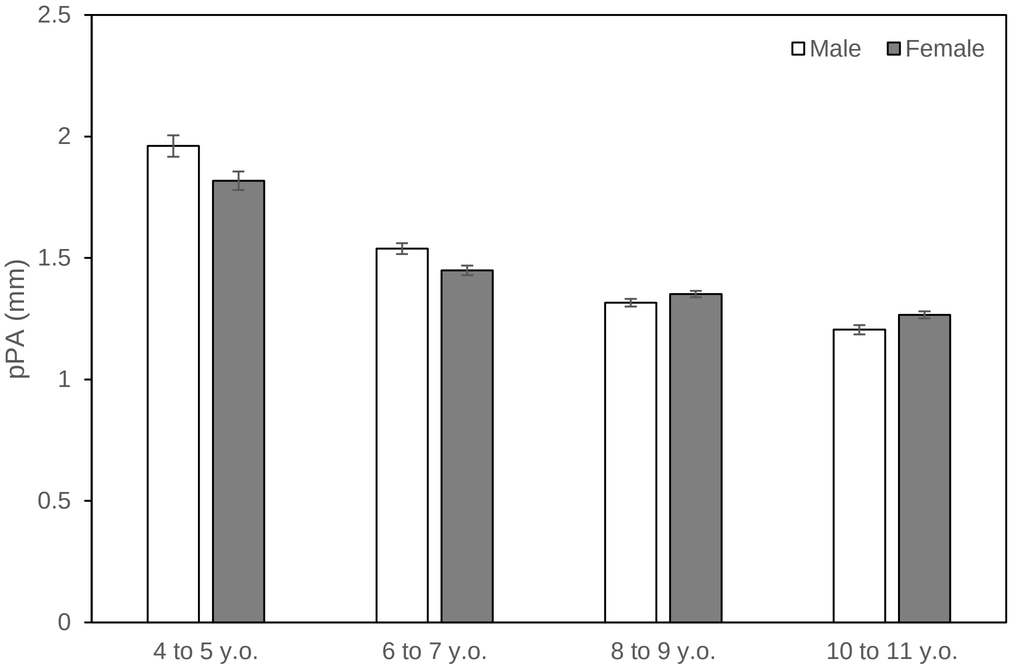


Figure 4. Results for penalised Path Accuracy (pPA) by age and sex.

pPA is a measure of spatial accuracy whilst tracing, adjusted to standardise for individual variation in speed. Statistically significant differences between age groups and sex were found on this outcome (both p<.001), with no significant interaction between them. Performance improved with increasing age and was consistently better (higher) in Females. Note: Error bars represent 95% confidence intervals.

1.4 Discussion

This study explored the psychological construct of ‘manual control’ in pre-pubescent children (4-11 years old). The scope of the study was confined to the control of a stylus held in the hand and explored three separate tasks that had different control demands: aiming movements, tracking and tracing. These findings provide the first detailed evaluation of the degree to which sex differences influence the development of manual control within this age range. The female population showed better performance on the aiming and the tracing task, with the higher performance observed in the aiming task being restricted to the youngest age groups and the advantage reversing to favour the males in the oldest age group. It seems reasonable to conclude that the younger females have superior control (i.e. are better able to guide the stylus) but these control differences are masked by the neuromuscular changes that occur as boys mature. This interpretation is consistent with the higher female skill levels observed across all age groups in the tracing task. The improved performance on the aiming task in the older boys suggests that the well-documented faster reaction times and shorter movement duration observed in adolescent and young adult males (Gur et al., 2012) first appear around the age of 10-11 years.

In contrast to the aiming and tracing task, there were no sex differences in the tracking task. It is always difficult to interpret a null finding, but the fact that differences emerged on the other two tasks suggests that any diversity between the sexes on the tracking task must be very small if it exists at all. Tracking tasks are known to be sensitive indicators of neurological deficit because they rely on sophisticated neural circuits to generate accurate predictions of an external target’s motion (Caeyenberghs et al., 2009; Caeyenberghs et al., 2010). Thus a limiting constraint on tracking performance is an individual’s ability to predict target motion meaning that differences in manual control can be masked because there is an upper limit on motion prediction. It has been reported previously that the normal right-left hand performance asymmetry is not found on manual tracking tasks for this reason (Raw et al., 2012b). Together, the results suggest that girls have superior manual control than boys (as indexed by the tracing task) but anatomical differences can wipe out this advantage, and superior performance disappears when tasks contain other constraints (e.g. a reliance on predictive neural circuits). These findings sound a note of caution for past and future studies that explore sex differences using complex ‘fine-motor tasks’ (e.g. handwriting), in part because such tasks become more prone to the effects of experience, but also because such tasks contain different control elements that might exert different effects outwith the researcher’s control.

The fact that sex differences in manual control were found raises the issue of whether the disparities warrant different educational approaches to handwriting tuition. It can be considered that, whilst the differences are reliable at the population level, they are too subtle to support the notion that boys and girls should be differentiated for handwriting education. First, the absolute differences and associated standardised effect sizes are too small (a few millimetres in tracing accuracy and a few fractions of a second in aiming movements) to make a practical difference. Second, the results show that other factors (e.g. anatomy, other task constraints) can swamp these control differences indicating that they are relatively small in nature. The tasks used were novel in nature and not culturally dependent. This gives some confidence that this study has elucidated underlying control differences between the sexes. Nevertheless, it is impossible to be certain that these findings do not reflect culturally imposed differences in developmental history. Regardless of how the manual control differences arise, these results suggest that it is hard to argue that girls should receive different educational opportunities than boys. In the context of the earlier introduction, these findings favour a ‘gender similarities’ hypothesis (Hyde, 2005). They demonstrate that sex differences in the motor, as in the cognitive domain, are highly task-specific and small in magnitude. This cautions against over-interpreting such disparities as reductive explanations for why differences in educational performance may arise between the sexes in the general population (Hyde et al., 2008; Halpern et al., 2007).

Finally, it should be emphasised that the present study has focussed exclusively on population differences (we deliberately applied transformations to ensure normal distribution of the outcome measures, account for outliers and used powerful statistical techniques that were robust to any violations of the homogeneity of variance assumption). There are good reasons to suppose that at an individual level there will be more boys than girls who have specific problems with eye-hand coordination (Eliot, 2011). DCD is more common in boys than girls, with estimates of the exact ratio ranging between 2:1 (Lingam et al., 2010) and 7:1 (Kadesjö and Gillberg, 1999). However, these findings do not support the interpretation of DCD as simply a characterisation of the motor skills of those children at one end of a continuum within the population (Lingam et al., 2009; Missiuna et al., 2011), which is consistent with a large number of studies that indicate pathological causes for DCD (Zwicker et al., 2010; Tsai et al., 2012). Children with DCD undoubtedly need additional educational support (Sugden and Chambers, 2003) but this should be based on identifying a child with a special need regardless of their sex. Individual differences in manual control are much greater than the relatively small differences identified between boys and girls as predicted by the gender similarities hypothesis (Cools et al., 2009).

Chapter 2: Measuring children's head movements and postural stability in visual and manual tracking tasks

Overview

Chapter 1 introduced a computerised test battery with the sensitivity to detect effects of gender on fine motor development. This chapter uses the technology used for this fine motor assessment but builds on it by incorporating measures of gross postural movement using a combination of off-the-shelf components and clinical measuring devices. With the synchronous fine and gross motor measurement possible with this system, an investigation into response of the maturing postural system to self-imposed perturbations (generated from a suprapostural task) could be performed.

2.1 Introduction

Childhood development is associated with the acquisition of an astonishing number of skilled behaviours. One reasonably well-documented example of a skill acquired over childhood is the ability to accurately direct gaze to stationary and moving targets - a skill that requires the coordinated movements of the head and eyes. Postural control develops over the course of childhood, transitioning from frequent falling and loss of balance to adult-like stable posture (Hatzitaki et al., 2002; Hayes, 1982). Manual dexterity is similarly refined over the developmental trajectory (Schneiberg et al., 2002). Monitoring the skill or efficiency of these behaviours over extended time periods would indicate a consistent, linear progression of the skill across childhood (Woollacott and Shumway-Cook, 1990). However, analysis over shorter time periods reveal chaotic transitioning to skilled behaviour, with skills being acquired, disappearing and then re-emerging (Kirshenbaum et al., 2001).

One reason that specific skills do not show steady progression toward mature behaviour is because of their interdependence on underpinning skills. Manual skills require accurate visual information so that execution errors can be detected and corrections implemented (Carlton, 1981). The quality of visual information is directly linked to the steadiness of the head which is determined by the stability of the postural base. Thus, poor postural stability will place an upper limit on the precision with which arm movements can be controlled, meaning that the development of improved manual skill must await better postural control (Berrigan et al., 2006). It is reasonable to suppose that the need for better manual skill acts as a driver to the postural system, which might explain why posture becomes increasingly stable over childhood once the basic level of ‘not falling over’ has been reached. It seems clear that carrying out skilled actions requires a synergistic relationship between the development of head, hand and postural control and therefore a complete picture of childhood development requires a consideration of how control of head, hand and posture develop in combination with one another.

The interdependence of visual-motor skills can also be illustrated by considering the how the two processes interact. Fixating between fixed targets often involves head movements, but movements of the head have consequence for postural stability (Schärli et al., 2013; Sugden, 1992). Likewise, moving the arm when standing causes shifts in the CoM - shifts that require postural compensation if the individual is to (i) remain standing and (ii) continue to obtain stable visual information for the purpose of accurately guiding the hand (Berrigan et al., 2006). These observations highlight the extent to which the control of posture, head and hand are intrinsically related. This relationship is of particular developmental importance as there are continuous maturational changes in the underlying mechanical properties of the body. Therefore, biomechanical changes resulting from this could be one reason why specific skills are seen to develop and regress over short time periods (Visser et al., 1998).

Given the important relationships between head rotation, hand movements and postural adjustment, there is limited research into how these systems become coordinated throughout childhood. One possible reason for the lack of extant studies is possibly due to the significant technical difficulties involved in measuring these movements simultaneously. Nevertheless, the recent advent of lower cost consumer electronics with wireless data streaming capabilities (e.g. Bluetooth) means that it is now feasible to start exploring the topic of the relationship between head, hand and posture. A system was developed capable of concurrently recording such data and a small scale study was conducted to determine the feasibility of using this system to provide insights into children’s motor development. The main interest of this project was the extent to which visually and manually tracking a target would produce postural changes. It was postulated that the visual tracking task might affect posture for two reasons. First, it is well established that visual information plays a role in the maintenance of postural stability and this role for vision is greater in younger children (Assaiante, 1998; Hatzitaki et al., 2002; Lee and Aronson, 1974; Shumway-Cook and Woollacott, 1985; Sparto et al., 2006; Wann et al., 1998). Thus, the allocation of visual attention to a local moving target may impact upon the ability of the system to use other visual information for postural maintenance. Second, posture might be affected if participants recruit head movements when tracking the target because of the mechanical changes associated with head movements causing shifts in the body’s CoM. Whilst individuals were able to visually track the target using just their eyes, it has been shown that such tracking often also involves head movements (Stoffregen et al., 2006). The same logic led to the conclusion that tracking the target with the hand has the potential to cause a decrease in postural stability as movements of the arm will alter the body’s CoM. The extent to which posture is affected by such arm movements would depend on the ability of the system to utilise compensatory mechanisms. It is also possible, of course, that the attention resources required in order to manually track a target could influence posture if demands are also made on the cognitive resources involved in maintaining posture.

Recent investigations into the effect of visuomotor tracking on posture have used Head Rotation (HR) and CoP movement as the measures of postural response and stability (Schärli et al., 2012; Schärli et al., 2013). These provide the ability to interpret how the CoM and head movements are coordinated. In addition to the visual stimulus paradigm used in recent studies (Schärli et al., 2012; Schärli et al., 2013), collecting postural data under both visual and manual tracking tasks would allow exploration of the extent to which the addition of manual movement affected posture, beyond the destabilising effect of visual stimulus alone.

2.2 Method

2.2.1 Participants

34 healthy individuals with no previous history of ophthalmological or neurological problems formed an opportunistic sample. The participants were allocated into one of four age groups, 5-6 years (n = 8), 8-9 years (n = 10) and 10-11 years (n = 7) and a young adult (19-21 years) group (n = 9). The children were recruited from a local school in Leeds following permission from the Head of the school and the parents. The adults were undergraduate students who volunteered to participate for no recompense. All participants were right-handed as indexed by the hand they stated that they used to write. All participants gave their written informed consent, and the experiment complied with ethical guidelines approved by the University of Leeds ethical committee, in accordance with the Declaration of Helsinki.

2.2.2 Procedure

In all conditions, participants stood on a Nintendo WiiFit Balance Board (WiiFit) with their feet a shoulder width apart in front of a tablet PC which was placed 50cm from the participant on a metal stand, the height of which was adjusted to the elbow height of the participant. In the baseline conditions, participants stood for 30s with their eyes open and for 30s with their eyes closed. In the visual tracking task, the dot movement was identical to that described in section 1.2.3.1.1. (i.e. the tracking subtest of the CKAT test battery). For the visual tracking task, three separate trials were completed at one of three target speeds (see Table 6) and each trial lasted 30 seconds. In the manual tracking task, the participants attempted to keep the tip of a hand-held stylus on the centre of the target where the movement of the target was identical to that described for the visual tracking conditions. Trial order was pseudo-randomised across speed and trial type.

Table 6. Stimulus frequency parameters for the three tracking task speeds, plus resultant velocities and subtest detail

Speed	Horizontal Freq. (Hz)	Vertical Freq. (Hz)	Mean Resultant Vel. (mm/s)	Minimum res. Vel. (mm/s)	Maximum Res. Vel. (mm/s)
Slow	0.125	0.0625	41.9	28.6	61.1
Med	0.25	0.125	83.8	57.2	122.2
Fast	0.5	0.25	167.7	114.3	244.3

2.2.3 Measurement system

The system was created using a tablet PC (Toshiba Portégé M750) with integrated Bluetooth connectivity. The tablet was used to present the visual stimuli and capture movements of the hand-held stylus in the manual tracking task (Culmer et al., 2009). In order to obtain a measure of the degree of postural movement about the CoM, the WiiFit was used to measure the participant’s CoP. This device has been demonstrated to be sufficiently accurate to determine between group differences in postural movement (Clark et al., 2010; Young et al., 2010). The WiiFit was connected to the host PC via Bluetooth and measured the X and Y position of the participant’s CoP (Figure 5). Head rotation was measured using a head mounted orientation tracker. The three Degree of Freedom (DoF) orientation tracker

(MTx, XSens, Netherlands) was mounted to a stiff, lightweight, adjustable brace, strapped to the head of the participant and connected to the tablet via a USB cable. This device recorded static (angular position) and dynamic (rate of turn, angular acceleration) information in three orthogonal axes of rotation.

To ensure optimal bandwidth from all three devices, sample data were individually buffered and recorded to a separate data file for each device, with samples for each device individually time-stamped and synchronised to a common start time. Acquisition frequencies of 100Hz, 100Hz and 60Hz were achieved for the tablet screen, XSens and WiiFit respectively. All data were smoothed after collection using a 10 Hz zero-phase Butterworth filter (equivalent to a 16Hz fourth order filter).

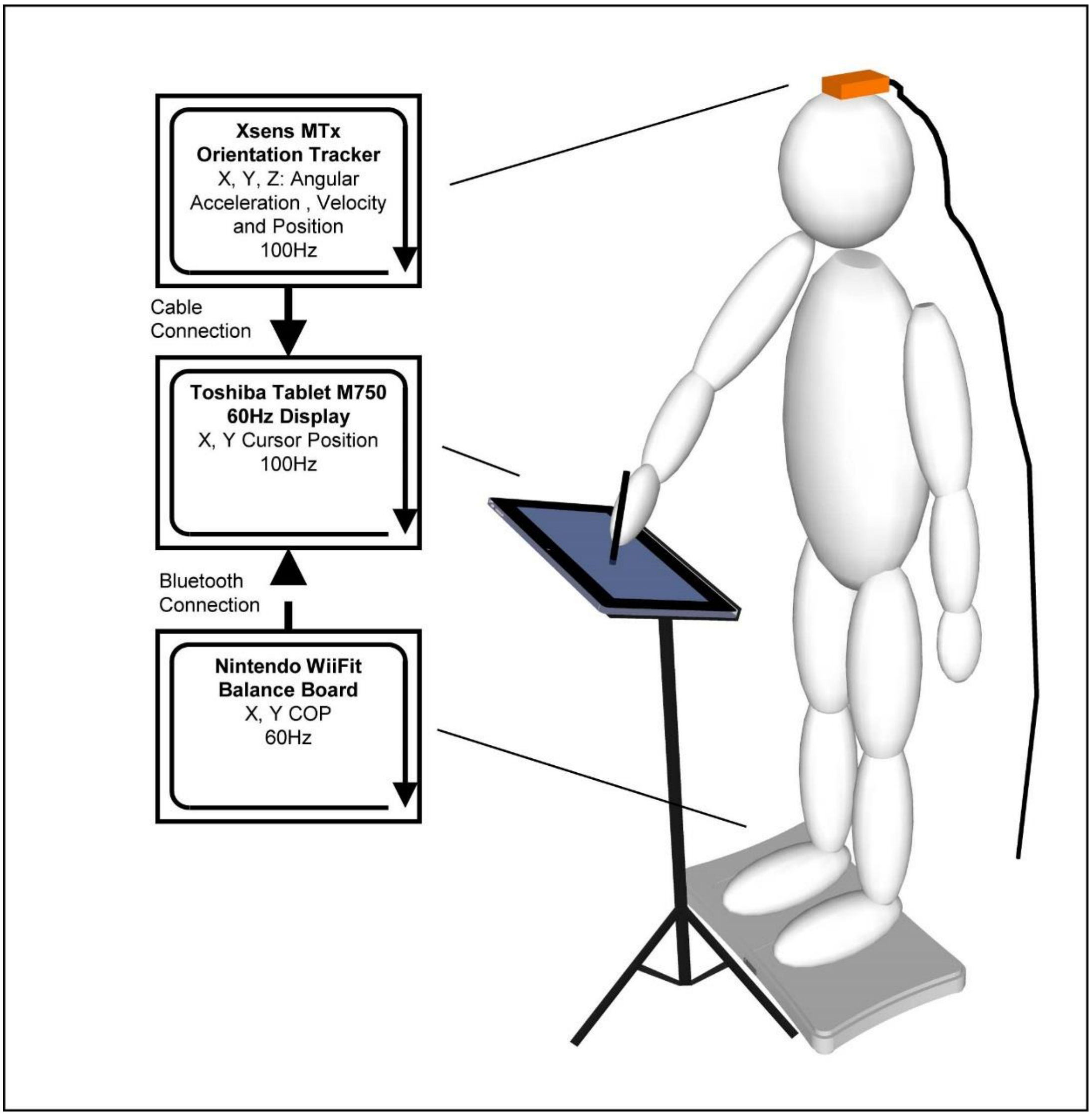


Figure 5. Schematic of the experimental setup.

Centre of pressure deviation was measured using a Nintendo WiiFit Board with the participants instructed to place their feet shoulder width apart. Visuomotor performance was measured using a tablet PC mounted on a platform adjusted to the elbow height of the participant. Head movement was measured using an XSens orientation tracker which was mounted to a rigid, adjustable strap on the head of the participant.

2.2.4 Metrics

HR was calculated as the summed angular rotation of the head about each of the three Cartesian axes over each target speed period. The summed angular rotation about all three axes measured by the XSens was the output metric for angular motion of the head. RMSe provided a measure of the distance the participant was from the centre of the moving target dot in millimetres and was calculated as the Root Mean Square of the distances between reference and participant input position over all samples in the trial. CoP movement was measured as the distance subtended by the CoP over each testing period. The CoP can be interpreted as the projection of the CoM of the participant onto the support surface (in this case the surface of the WiiFit). The time-course CoP movement can therefore be associated with the movement of the CoM of the participant.

2.3 Results

2.3.1 Visual tracking task

First, HR data when participants were asked to fixate the moving target was analysed. Inspection of Figure 6a suggests that there was considerably more HR with the moving target relative to baseline for the younger children but not the adults.

In order to formally test this observation, an ANOVA was used to compare baseline trials with the fast target trials (within participant factor) as a function of age and confirmed a significant interaction between condition and age (F (3, 31) = 3.041, $p < .05$, $\eta^2_{p\,=}$ .23). In principle, the participants could have carried out this task by tracking the target with just their eyes (in which case there should be no difference between the baseline trials and the moving targets). Indeed, inspection of the adults’ data shows that there were minimal head movements associated with maintaining fixation on the moving targets. A test was performed to establish whether the moving targets produced increased HR relative to baseline in the adults. All four speeds (baseline, slow, medium and fast) were entered into a one way ANOVA which confirmed there was no effect of target speed on HR (F (3, 24) = 1.004, p =0.4, $\eta^2_{p\,=}$ .11). The effect of the moving targets on HR as a function of age was then explored. A reliable interaction between age and speed was found, reflecting the pattern seen in Figure 6a whereby young children move their head when tracking the moving targets, particularly when the target moved quickly (F (6, 62) = 2.816, $p < .05$, $\eta^2_{p =}$ .22). Main effects of speed (F (2, 62) = 16.410, $p < .001$, $\eta^2_{p =}$ .35) and age (F (3, 31) = 7.186, $p < .001$, $\eta^2_{p =}$ .41) were associated with this interaction.

It was predicted that head movements would be associated with changes in the CoP (because of changes caused by or in response to the shifts in the body's CoM) and thus a similar pattern of results was expected when looking at changes in the CoP as a function of fixating the moving target. This prediction was borne out by the data (as shown in Figure 6b) and confirmed by testing the differences between the baseline and fast trials (F (1, 31) = 9.087, $p < .005$, $\eta^2_{p =}$ .23). Exploration of the moving target data showed that young children produced greater changes in the CoP relative to adults when visually tracking the moving targets and this effect was exaggerated when the target was moving quickly (F (6, 62) = 2.778, $p < .05$, $\eta^2_{p =}$ .21). Main effects of speed (F (2, 62) = 10.759, $p < .001$, $\eta^2_{p =}$ .26) and age (F (3, 31) = 8.488, $p < .001$, $\eta^2_{p =}$ .45) were associated with this interaction. The capacity of moving targets to increase CoP movement relative to baseline was investigated in the adults by entering all four speeds (baseline, slow, medium and fast) into a one way ANOVA, and as expected there was no effect of target speed on CoP (F (3, 24) = 1.000, p = .41, $\eta^2_{p =}$ .11).

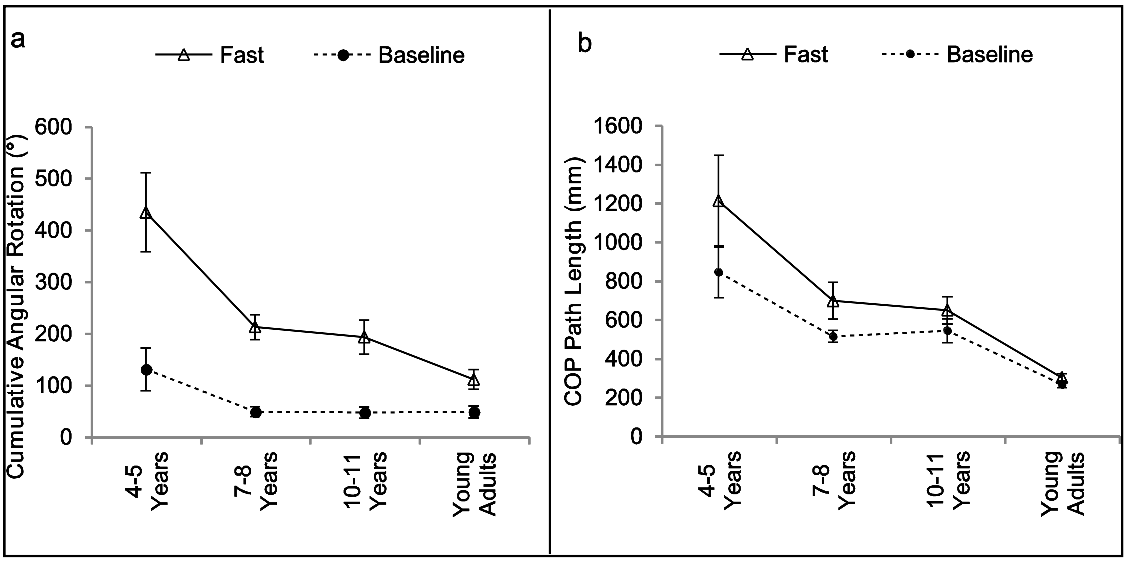


Figure 6. Head rotation and CoP deviation

Head rotation (left panel) and CoP path length (right panel) plotted as a function of age showing baseline and fast dot speed only. Both panels represent the synchronous cumulative movement observed at the head and base of support for a 30s trail duration.

2.3.2 Manual tracking task

The manual tracking task required participants to follow the target with their hand. The effects of speed and age were explored when considering the manual tracking accuracy data alone. A reliable effect of speed was found (F (2, 52) = 239.05, p < .001, $\eta^2_{p\,=}$ .90) whereby faster moving targets caused poorer tracking performance (Figure 7). There was also a reliable effect of age (F (3, 26) = 12.42, p < .001, $\eta^2_{p\,=}$ .59), reflecting the fact that older children showed better tracking performance than younger children (Figure 7). There was no reliable interaction between age and speed.

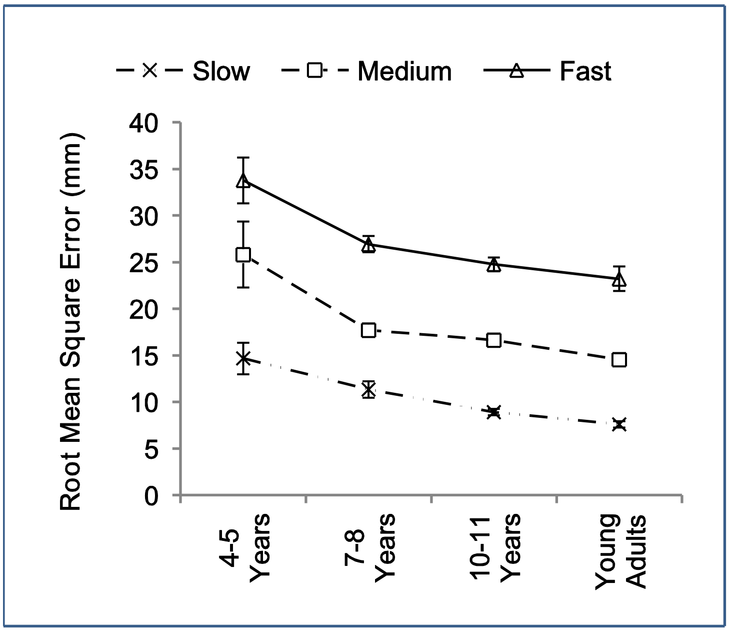


Figure 7. Hand tracking accuracy
Measured as the Root Mean Square 2D positional error over a 30s trial duration between the centre of the moving target dot and the participant's stylus position plotted as a function of age and moving dot speed.

Postural behaviour during the manual task was then explored. First, an 'omnibus' ANOVA was performed to compare the posture measures during the visual tracking and manual tracking tasks to see if it was possible to detect differences between tasks (speed was removed as a factor from this analysis). A reliable effect of task was found for both the HR data (F (1, 31) = 5.326, $p < .05$, $\eta^2_{p\,=}$ .15) and the CoP movement data (F (1, 31) = 15.888, $p < .001$, $\eta^2_{p\,=}$ .34) suggesting greater postural movement during the manual task (Figure 8).

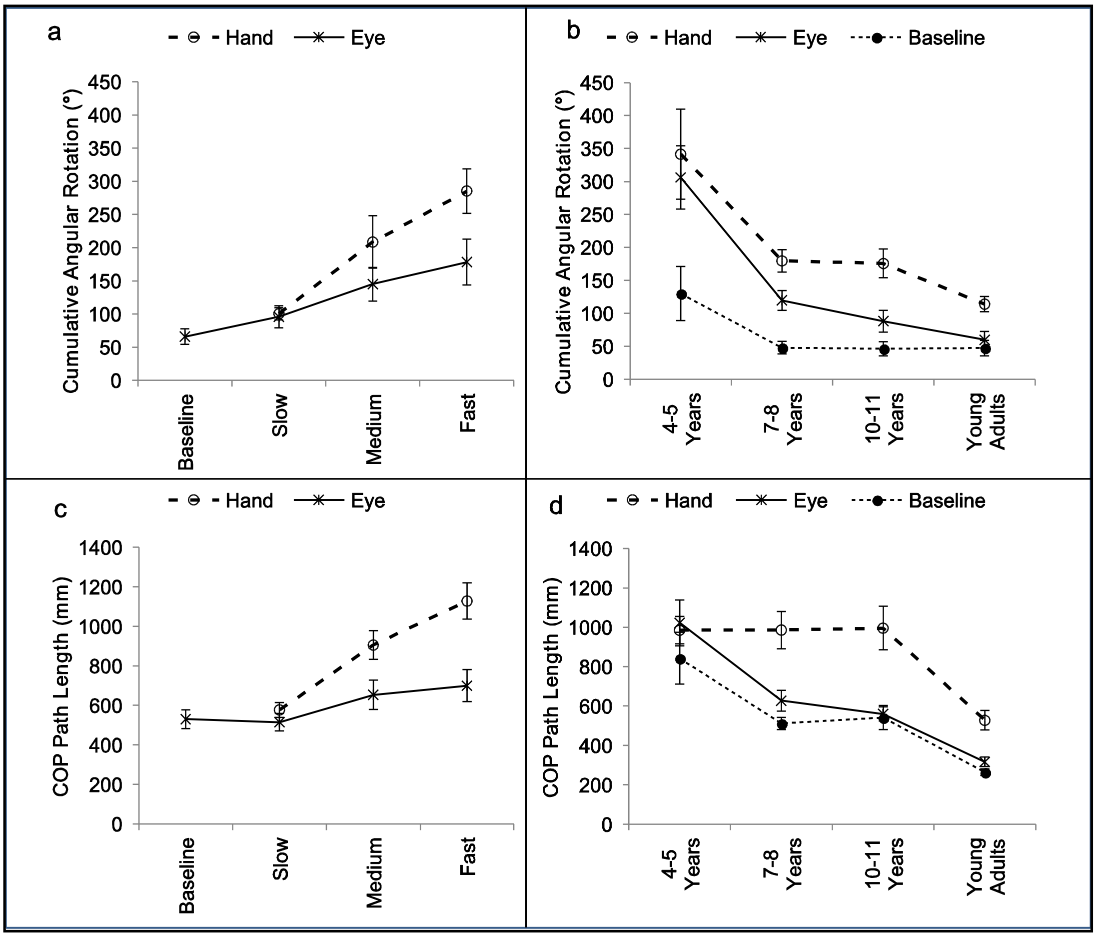


Figure 8. Head rotation and CoP deviation plots.

All figures represent the cumulative movement observed at the head and base of support for a 30s trail duration. Baseline is a vision-only condition where the participants observed a stationary dot in the centre of the screen for 30s. Upper left panel, head rotation plotted as a function of dot speed and tracking type (tracking the dot with eyes only, or with hand and eyes). Upper right panel, head rotation plotted as a function of age group and tracking type. Bottom left panel, CoP deviation plotted as a function of dot speed and tracking type. Bottom right panel, CoP deviation plotted as a function of age and tracking type.

The effect on the HR measure mirrored performance on the manual tracking task, with a reliable effect of speed (F (2, 60) = 26.777, $p < .001$, $\eta^2_{p\,=}$ .47) with faster moving targets causing greater movement of the head (Figure 8a). There was also a reliable effect of age (F (3, 30) = 4.099 $p < .01$, $\eta^2_{p\,=}$ .29) reflecting the fact that older groups showed reduced head movements compared to younger groups (Figure 8b). There was no reliable interaction between age and speed (though it approached significance; F (6, 60) = 2.064, $p = .07$, $\eta^2_{p\,=}$ .17).

Finally the question of whether the manual tracking task affected the CoP movement index of postural stability was addressed. The pattern was identical to the HR measure with a reliable effect of speed (F (2, 60) = 49.157, $p < .001$, $\eta^2_{p} = .62$) whereby faster moving targets causing more CoP movement (Figure 8c). There was also a reliable effect of age (F (3, 30) = 5.306, $p < .01$, $\eta^2_{p} = .35$) reflecting the fact that older groups showed better postural stability than younger groups (Figure 8d). Again there was no reliable interaction between age and speed (though this also approached significance; F (6, 60) = 1.907, $p = .09$, $\eta^2_{p} = .16$).

2.4 Discussion

This study investigated the development of postural control under varying visual and manual task demands. The approach was to take synchronous measurements of head, hand and CoP movements in order to explore the relationship between postural stability and visuomotor task performance. The results across all measures showed clear improvements in performance as a function of age group. Thus, the youngest children showed the poorest levels of performance when manually tracking the presented target, with the age differences becoming magnified as the task became harder (when the target moved faster). The youngest children also showed higher levels of postural instability as indexed by the CoP measure. These results were not surprising but allowed the developmental course of the relationship between movements of the head and hand and postural stability to be investigated. These findings showed that tasks which elicited movements of the head caused displacement of the CoP in young children, supporting the hypothesis that head movements affect postural stability. In all groups, the manual tracking task caused CoP displacement which provides further support for the hypothesis that movements of the head and hand have consequences for the postural control system. The notable finding was that displacement of the CoP decreased as a function of age in tasks that required movements of the arm (i.e. the manual tracking tasks).

There are two possible mechanisms by which humans might improve their balance abilities over the developmental trajectory. First, the system may become faster in detecting changes in posture (through vision, kinaesthesia, tactile stimulation and vestibular stimulation) and more able to rapidly generate corrective movements in response to these changes. There is no doubt that such refinements occur over childhood and help improve stability in response to unexpected perturbations (Sugden, 1992). Improvements in these reactive feedback processes would allow the postural system to maintain greater stability when displacements of the CoM are produced by planned changes in head and arm position. The extent to which movements of the head and arm destabilise an individual would then be proportional to the time taken to respond to the input (i.e. the shift in CoM produced by the effector movements). Second, the system may develop predictive control mechanisms where changes in the CoM are predicted by internal models and counteracted by postural adjustments that occur synchronously with the head and arm movements. The presence of such anticipatory adjustments would result in minimal displacement of the CoP during planned movements of the head and hand. This feed-forward method of postural control requires the system to learn the relationship between movements of the head and hand the resultant changes in the CoM.

Inspection of the data provides evidence in support of the notion that predictive mechanisms develop over childhood. The tasks that required participants to move their head and hands had a much smaller impact on the CoP displacement in adults than in children. If improved stability was a result of better reactive mechanisms in adults then one would not expect the CoP measure to decrease (as the initial displacement would still be present even if it was corrected in a short period of time). It should be noted that an alternative explanation is that the feedback control mechanisms have developed very short latencies.

Thus, one plausible account is that the reduced displacement of the CoP with increased age suggests that humans develop the ability to generate stabilising forces that counteract the CoM changes associated with given head and arm movements. These results are consistent with a large body of literature that suggests humans have sophisticated internal models (Wing et al., 1997) and that these models develop over childhood (Shadmehr and Mussa-Ivaldi, 1994). For example, human adults alter their fingertip forces in a manner that anticipates changes in the momentum of a handheld object when they move the object from side to side or up and down (Flanagan et al., 1993).

The visual tracking task employed did not necessitate the use of head movements - it was possible for the participants to track the targets using their eyes. The results indicate that this was the strategy adopted by the adults as head displacement did not increase from baseline values in the visual tracking task for this group. The fact that eye movements were not measured meant there is the possibility that the older participants did not follow the instructions and failed to maintain fixation on the target. It seems unlikely that the groups got worse at following the instructions as they got older (if anything the opposite would be expected). It therefore appears that children have less ability to decouple eye and head movements when pursuing a target - the head has a greater role in adults when gaze is shifted to maintain foveation of a moving target. The fact that children are less able to compensate for these head movements means that visually tracking a moving target creates postural demands for children. It is possible that the less stable posture created by movement of the head is one of the drivers that results in adults being more likely to track the target with their eyes in this type of task.

In the introduction to this study it is suggested that childhood development does not follow a neat linear progression from unskilled to skilled behaviour. The nonlinear nature of the developmental progress can be seen within the data collected. For example, the oldest group of children show clear improvements in their ability to maintain stable posture when visually tracking a target but have almost identical CoP displacement in the manual tracking task. This pattern of results is consistent with the notion that different skills develop at different rates, with progression in one skill often dependent on another skill improving first. The synergistic relationship between head, hand and postural control appear to provide a good model of this dynamic interdependency. In fact, the relationship is further complicated by the anatomical changes that occur over the developmental period, meaning that the system needs to compensate for changes in mass, lever length, distribution of weight, etc. This study was designed to be a ‘proof of concept’ using small participant numbers tested in fairly coarse age bands, suggesting that the concept has been validated. These measurements can provide a sensitive and powerful tool for investigating the complex dynamical changes that occur over childhood and understanding the control strategies adopted by the human central nervous system. In summary, a transition from compensatory postural adjustments in children to anticipatory feed-forward control processes in adults was identified. The fact that the portable equipment has the fidelity to detect changes in postural behaviour represents a significant opportunity to identify children who have deficits in postural control. Thus, this equipment has the potential to allow identification of children with movement problems early in their development and help in the understanding of control strategies in both normal and abnormal development.

Chapter 3: A new tool for assessing head movements and postural sway in children

Overview

Chapter 2 introduced a platform system capable of synchronous fine and gross movement assessment. An obstruction to the large scale deployment of this technology is the reliance on clinical measuring equipment to measure postural sway at head (the Xsens sensor). To address this, the present chapter describes the development of a motion capture system capable of acquiring head movement data using off-the-shelf products. Furthermore, limitations associated with using consumer goods for clinical measurements are addressed using acquisition, calibration and filtering techniques described herein. Thus, objective, quantitative assessment is possible, in the environment of interest (here, the classroom) and on a scale not readily accessible using clinical-grade motion capture or force platform technology.

3.1 Introduction

Culmer et al. (2009) described a system (the Clinical Kinematic Assessment Tool (CKAT)) capable of providing objective data on a range of visuomotor tasks. CKAT offers the possibility of obtaining powerful measures of an individual’s manual motor skills with the ease and convenience of traditional pen-and-paper tests. The advantages to educational establishments of such measures are clear - schools use handwriting level as a direct outcome measure for their pedagogical activities, but also rely on children’s writing and typing skills for assessment and teaching across the whole curriculum. Moreover, manual skill is required in numerous situations other than tasks involving handwriting within schools: young children take part in art and crafts, cutting out shapes and painting whilst older children need to hold test tubes and play musical instruments. Nevertheless, a number of children have motor deficits and their educational progress suffers as a direct result of these problems. Thus, the identification of children with motor skill deficits is of paramount importance. It is therefore unsurprising that CKAT has been deployed in Born in Bradford (BiB), a large scale cohort study that is attempting to understand the factors related to maternal and child health that can impact negatively on a child's educational and health development (http://www.borninbradford.nhs.uk). The success of the CKAT system is witnessed by the fact that it has been successfully used to test over 1700 children in the past six months as part of the BiB project (with another 12,000 children due to be tested over the next three years).

The CKAT system provides incredibly useful data regarding a child's fine-motor skills. One limitation of the system, however, is that it does not assess an individual's gross-motor abilities. It is probable that an individual with fundamental deficits in postural control will have difficulties in developing manual abilities (because a stable platform is required to generate skilled hand movements (Berrigan et al., 2006)) and thus the CKAT system may still identify this problem. Nonetheless, it is clearly desirable that such deficits can be distinguished so that they can be directly assessed. Indeed, the measurement of postural stability is considered central to a thorough assessment of an individual's motor status (Sugden, 1992). It would be desirable, therefore, to test the postural stability of children as well as measure their manual skills in developmental studies (such as the BiB project).

The difficulty with incorporating tests of gross-motor skills is that there is no low cost option available that provides the quality of information equivalent to the data generated by the CKAT system. The traditional method of assessing postural stability relies on standardised test batteries such as the MABC (Henderson et al., 1992). The MABC is a useful tool and has the advantage of being relatively low cost (once the price of the test has been paid). Nevertheless, the MABC requires skilled practitioners (e.g. qualified psychologists or physiotherapists) to administer and is time consuming. Moreover, the test relies on someone observing a child and timing their ability to maintain a given posture - and this approach introduces problems. It seems reasonable to suppose that the best measures of postural stability involve a child adopting a natural standing position but the limitations of observational techniques means that the MABC requires the children to stand (for example) on one leg whilst the examiner observes how long this posture can be maintained. This makes testing more difficult and can be stressful for children who are aware that they are being ‘tested’ (and this might invoke anxiety which will add noise to the measurement process). The alternative to using pen-and-paper batteries such as the MABC is the deployment of electronic measurement equipment such as force platforms. There is a wide range of commercially available force platforms that can provide extremely useful measures related to changes in the CoM of an individual standing on the force plate. These systems are typically located in research laboratories and have provided great insights into the neuroscience of postural control in humans. The quality of the data supplied by these systems is not in doubt, but they are expensive and not readily portable (they generally require special mounting within the floor of the research laboratory).

The aim of this study therefore was to design a system that had the portability and low cost of a standardised test battery but which could supply data of the quality normally collected within research laboratories rather than school settings. One low cost device that recently has become popular for measuring posture is the Nintendo (Nintendo, Kyoto, Japan) WiiFit board. It has been shown that this device is an adequate substitute for force platforms in the measurement of postural sway (Clark et al., 2010; Young et al., 2010). Nevertheless, there are factors specific to the application of the system in children. The lower fidelity of the hardware, coupled with a lower signal/noise ratio (owing to the low mass of the participants and the nature of the measured tasks) makes between-group identification of postural differences difficult. These engineering challenges were met via the development of filtering and analysis techniques. A key requirement of this system would be that it could simultaneously measure head movements. The rationale was that a major goal of the human postural system is to ensure the stability of the head (so that stable visual information can be used to guide skilful interactions with the world). On these grounds it was conjectured that measurements of head stability would provide an index of an individual’s ability to maintain stable posture. Thus movements of the head during stationary stance might be a useful measure when trying to identify individuals with movement problems (perhaps in conjunction with measures of the CoP). Moreover, data on how the head moves during stationary stance might shed light on the neuroscience of postural control. The problem with the data generated by force platforms is that they provide only an indirect measure of how the CoM is moving. Information on how head movements relate to changes in the CoP might provide insights into the underlying control mechanisms supporting posture. This might be particularly interesting when exploring tasks that require head movements (e.g. visual or manual tasks where moving targets need to be tracked for successful performance) (Schärli et al., 2012).

There are some commercial systems available that can provide data on head movements. For example, inertial motion capture systems have been developed to incorporate micro-electronic accelerometers and gyroscopes and can be made small enough to be worn on the head (Zhou and Hu, 2008). These systems typically use three orthogonal accelerometers to specify an acceleration vector that is transformed into a consistent (typically gravitational) frame of reference using data from three gyroscopes. There is a question about whether the rotational data provided by inertial sensors is optimal for measuring head movements. The difficulty is that rotational head movements caused by sway around the ankle subtend only a few degrees and may therefore be less indicative of postural movement than changes in head position. Integrating the accelerometer signals twice to obtain displacement would enable crude calculation of positional data but a low signal/noise ratio and twofold integration yields inaccurate results. An alternative approach is to use a magnetic motion capture system (such as the Ascension ‘Flock of Birds’ system) that derives a 3D position from a magnetic field in three orthogonal planes (Welch and Foxlin, 2002). These systems have the advantage of being light and compact so they can be readily placed on the head (though the cables can interfere with head movement). These systems are expensive, and require technical expertise to operate. The systems are also sensitive to ferrous objects disturbing the magnetic field within which the sensors operate. The system can be calibrated to account for simple static ferrous objects but in less controlled environments (e.g. schools) this is impractical. Finally, the use of optical motion capture systems would provide highly accurate positional data over a large number of points and over a large measurement volume. Optical motion capture systems have the advantage that they can operate wirelessly, reducing measurement interference and reducing the risk of accidental damage of the equipment. Furthermore, some systems are portable and can be calibrated in-situ. However, optical systems are complex to set up, costly and require a relatively large amount of space in which to operate. The calibration of the portable optical motion capture systems is also extremely sensitive to accidental shifts in camera position during testing, something that is difficult to guarantee when testing children in a relatively uncontrolled environment.

The aim of this study was to design a low cost wireless system that could provide accurate data on head movements concurrently with data collection involving the Nintendo WiiFit board. The system developed was then tested in two UK primary schools to ensure that the system could be deployed easily by non-specialist staff and could generate sensible and useful data.

3.2 Description of the head tracking system

Clinical motion capture equipment is extremely effective in accurately measuring the spatial position of reflective markers across a wide measurement volume, typically achieving sub-millimetre measurement error over $2m^3$ measurement volumes (Richards, 1999). Moreover, the passive markers used in some optical motion capture systems facilitate wireless spatial measurement of the points of interest on the body. Recent studies have used consumer electronics as a platform for human movement measurement and as a basis for gesture-based human computer interaction in the form of the Nintendo Wii, and specifically its controller, the WiiMote. Broad similarities between the WiiMote technology and clinical-based motion capture systems have resulted in the development of a number of applications of rudimentary stereo-vision systems based on the WiiMote controllers. The WiiMote comprises an Infra-Red (IR) camera capable of resolving IR point sources in the 800-950nm wavelength range and relaying only the pixel coordinates (at a resolution of 1024 x 768 pixels) of up to four IR point sources. Thus, for the available communication bandwidth, the WiiMote is capable of high resolution and high capture rate of IR point pixel coordinates.

In addition to its similarity on a functional level to clinical motion capture systems, the Nintendo Wii controller (WiiMote) has two main properties which made it particularly amenable to wide-scale deployment outside the laboratory environment: i) The WiiMote connects wirelessly using the Bluetooth communication protocol which, coupled with battery power, avoids the requirement for cable routing and allows for flexible equipment placement, and ii) The relatively low cost of the Nintendo WiiMote devices (c. $20/£15) ensures that the methods developed here have scalability in their application. Nevertheless, if the low cost components failed to have the degree of precision needed their cost would be irrelevant, so a suitable calibration process capable of compensating for the comparatively low optical quality of the WiiMote cameras is required.

The measurement resolution and accuracy of any optical motion capture system is proportional to the size of the measured volume. Previous systems developed using the WiiMote have been created as a platform for human/computer interaction (Modroño et al., 2011; Scherfgen and Herpers, 2009). Owing to their necessarily large measurement volume (to capture the extent of large movements) the accuracy of WiiMote derived systems, although comparable to much more expensive equipment, is correspondingly low (Hay et al., 2008). The measurement of head movement in quiet standing would require a small measurement volume.

By exploiting the relationship between measured volume and accuracy, the WiiMote-derived motion capture system could be optimised for small measurement volumes, similar in principle to how clinical-grade equipment can be reconfigured to measure small volumes at sub 100µm accuracies (Windolf et al., 2008). Thus, the accuracy of measurement could be increased sufficiently to enable sensitive detection of head movements and changes across the developmental trajectory.

In addition to the accuracy requirements of the equipment, it was important to consider that this system would be operated by non-expert users. To achieve this, a stereo vision module was manufactured and delivered which integrated two pre-calibrated WiiMote controllers into a tripod-mounted housing and connected wirelessly to the host computer (Figure 9). This simplified system allowed deployment outside of the laboratory setting and avoided the requirement to calibrate the system in-situ. Furthermore, suitable error checking software comprised within a simple user interface further simplified operation of the equipment.

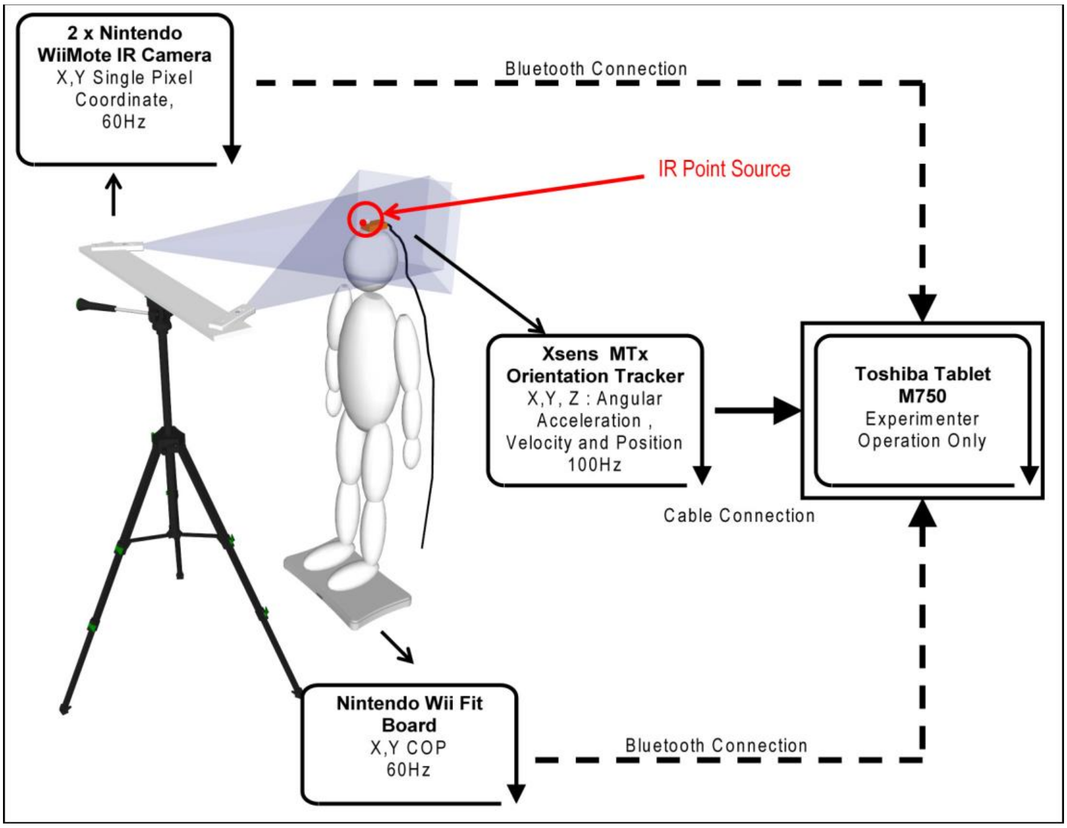


Figure 9. Motion Capture System schematic.

A three-dimensional motion capture system was developed using a pair of Nintendo Wii controllers connected to the host computer via Bluetooth and to a suitable calibration routine which calculated the internal properties of each IR camera. A second calibration was then performed which calculated the relative orientation and position of the cameras with respect to each other. The Wii controllers then relay the X and Y coordinates of this source at 60Hz to the host PC. By triangulating the results from the two controllers, the IR source can be located in 3-dimensional space in the same manner as stereoscopic vision. For the purposes of this study, an XSens device was mounted to the same head strap as the IRED. Measures from this device were included to provide an initial comparison between angular and positional measures of postural sway and validation of the new motion capture system against clinical motion capture equipment.

3.3 Calibration

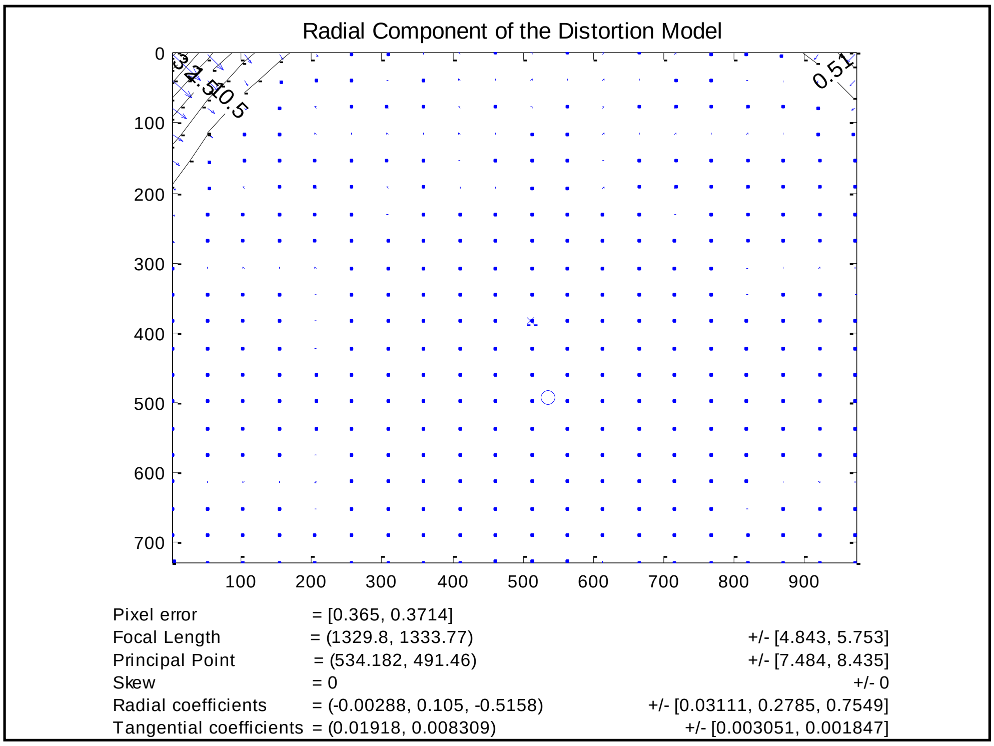
Error in locating a triangulated point in space can arise from two specific optical properties of the stereo system: errors resulting from the distorting effect of the lenses on the observed image (intrinsic errors), and errors that occur due to inaccurate knowledge of the position and orientation of the cameras with respect to each other (extrinsic errors). Thus, improvement in the accuracy of determining the triangulated position is dependent on being able to correct for the optical distortions and also to accurately calculate the position and orientation of each camera through intrinsic and extrinsic calibration of the system. This study uses the widely used camera calibration toolbox (Bouget, 1999) to identify, and compensate for lens distortions. To calculate the internal parameters of the camera, this toolbox uses the method proposed by Zhengyou (Zhengyou, 1999) where an image of a checkerboard calibration pattern is taken in a range of orientations and positions with respect to the camera. Computer vision software identifies point coordinates at the corners and intersections of the checkerboard pattern. Differences between the point locations observed on the distorted image compared against those anticipated where the camera distortions are not present (determined from the geometry of the grid pattern) are fed as errors into an optimisation model. The model determines the lens distortion (radial, tangential and skew), focal length, image principal point and pixel distortion that best describes the grid distortion observed in the camera image, resulting in a matrix of intrinsic camera properties which can then be used to correct for the distortions.

For stereo calibration, an image of the calibration grid can be taken in both cameras, and the same computer vision technique can then identify corresponding points between the images (after the images in each camera are corrected for lens distortion). Differences in the position of corresponding points between camera images then serve as inputs into a stereo calibration model. The optimisation determines the relative translation and orientation of the cameras that best describe the observed point location differences between the images. Thus, with the relative translation and orientation of the cameras known, a straightforward triangulation calculation can be performed using the pixel coordinates from both images coupled with the known optical properties of the stereo vision system to calculate the three-dimensional position of the point in space.

Implementation of the original grid-based calibration toolbox routine was not suitable for deriving the WiiMote camera properties as there is no access to the camera image. A grid could theoretically be reconstructed using a series of IR diodes in a planar pattern, but the WiiMote is only capable of tracking up to four IR diodes at a time. An alternative could be to sequentially illuminate four IR diodes which are part of a planar grid pattern. This could build up a patchwork grid pattern of coordinates which, when recombined into a single image, would provide a calibration grid reference either serving as an input into a calibration routine, or as a method of establishing direct mapping between pixel and three-dimensional coordinates (Kim et al., 2012). The more elegant solution of a simple four point calibration board was adopted, whereby the four point IR sources were used as “corner points” of a grid with no intermediate grid points. By using a large number of these grid images, there were sufficient observed error inputs for the calibration optimisation model of lens distortion properties to converge. The original grid-based calibration routine was therefore modified to use data in the form presented by Bakstein (Bakstein, 2000). Through optimisation, the calibration software solved an internal camera model developed by Haikki and Silvenen (Heikkila and Silven, 1997) which comprised parameters for lens distortion (radial (Figure 10), tangential (Figure 11) and skew, focal length, image principal point and pixel distortion. With the optical properties of the lenses determined (Figure 12), the same calibration board was then used as a basis for the stereo calibration technique where the optimisation routine was modified to accommodate information from a large number of board images. Convergence of the stereo calibration optimisation yielded the relative positions and rotations of the cameras which best described positional (pixel coordinate) differences of corresponding points between camera images.

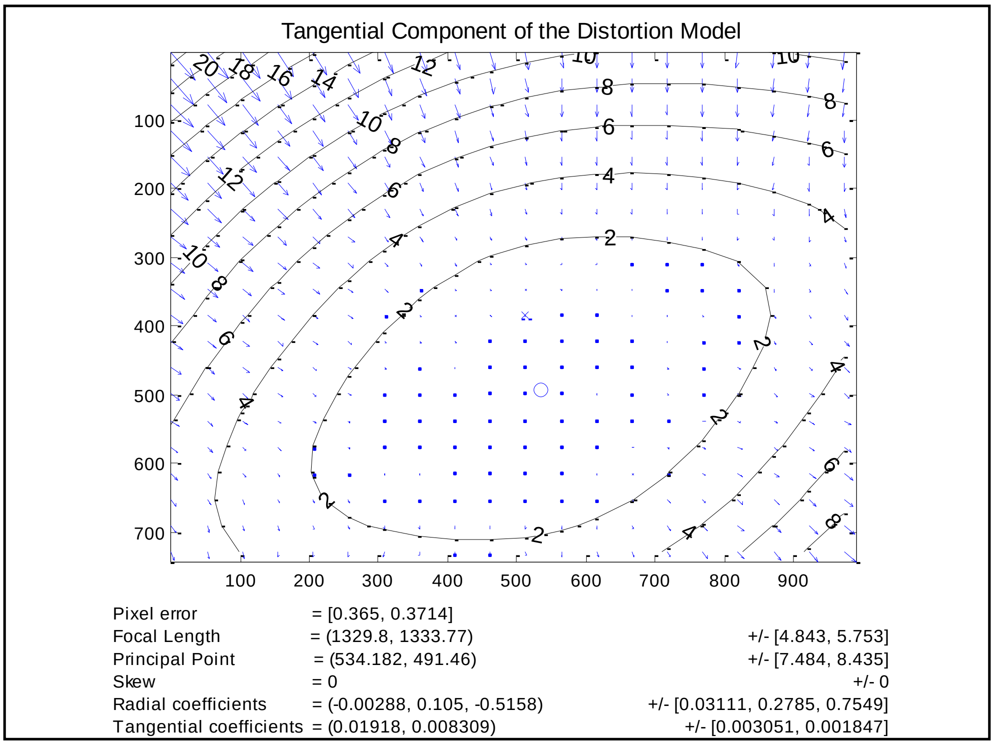
3.3.1 Calibration for intrinsic camera properties

A calibration image capture sequence acquired snapshots of a four-IR diode calibration board powered using a 9V battery. The four IR diodes were placed in a 150mm square formation. The calibration required the capture of between 250 and 350 “images” (2D coordinates of the IR diodes in the camera image plane) of the stationary calibration board in a range of orientations, distances and positions across the image to enable successful convergence of the calibration optimisation routine. The calibration images were captured at 0.5Hz intervals. Three calibrations were performed on each camera in the stereo pair and a script contained within the calibration toolbox was used, which was able to combine the separate calibrations to improve accuracy of the overall model solution. The numerical errors were calculated for each distortion parameter approximated to three standard deviations of the respective parameter. Calibrations where any parameter value of zero was within three standard deviations of the calculated value were discarded, as it was indicative of a failed optimisation.



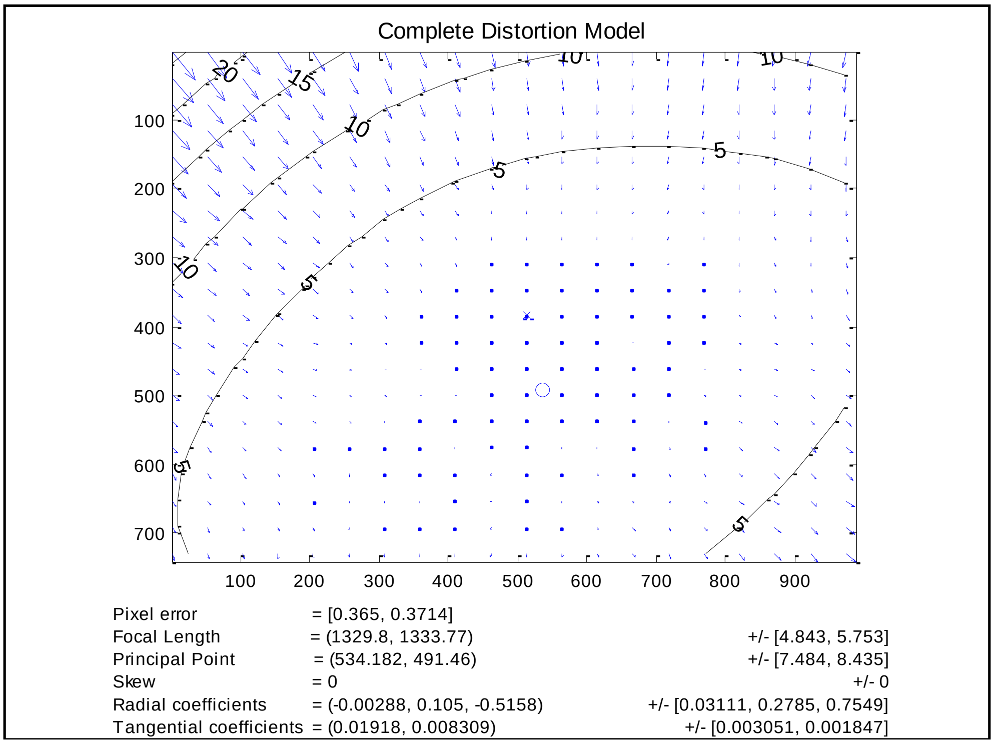
```
Pixel error             = [0.365, 0.3714]
Focal Length            = (1329.8, 1333.77)                         +/- [4.843, 5.753]
Principal Point         = (534.182, 491.46)                         +/- [7.484, 8.435]
Skew                    = 0                                                    +/- 0
Radial coefficients     = (-0.00288, 0.105, -0.5158)    +/- [0.03111, 0.2785, 0.7549]
Tangential coefficients = (0.01918, 0.008309)               +/- [0.003051, 0.001847]
```

Figure 10. Example intrinsic calibration result, radial component of model distortion



```
Pixel error            = [0.365, 0.3714]
Focal Length           = (1329.8, 1333.77)                          +/- [4.843, 5.753]
Principal Point         = (534.182, 491.46)                         +/- [7.484, 8.435]
Skew                   = 0                                                       +/- 0
Radial coefficients    = (-0.00288, 0.105, -0.5158)         +/- [0.03111, 0.2785, 0.7549]
Tangential coefficients = (0.01918, 0.008309)                  +/- [0.003051, 0.001847]
```

Figure 11. Example intrinsic calibration result, tangential component of model distortion



```
Pixel error            = [0.365, 0.3714]
Focal Length           = (1329.8, 1333.77)                          +/- [4.843, 5.753]
Principal Point         = (534.182, 491.46)                         +/- [7.484, 8.435]
Skew                   = 0                                                       +/- 0
Radial coefficients    = (-0.00288, 0.105, -0.5158)         +/- [0.03111, 0.2785, 0.7549]
Tangential coefficients = (0.01918, 0.008309)                  +/- [0.003051, 0.001847]
```

Figure 12. Example intrinsic calibration result, combined (complete) model distortion

3.3.2 Calibration for extrinsic camera properties

The two WiiMotes were integrated and fixed to a stereo vision housing to facilitate ease of transport, speed system setup and prevent accidental relative movement of the cameras post-calibration. Both cameras had been previously calibrated to obtain their intrinsic camera parameters. The board was manufactured from reinforced MDF which housed both Wii controllers in slots, cut-out such that they were in opposition at an angle of 25° from the midline of the board (see Figure 13).

Figure 13. Camera construction on tripod-mounted board

Horizontal opposition of the WiiMotes was intended to enhance accuracy in the depth direction (at the expense of infinite focal depth) by ensuring deviations in the depth direction yielded greater migration of the resolved IR point across the image planes in both cameras. The centre of the camera beams aligned at a distance of 1m from the front of the board - the intended position of the participant's head.

To determine the stereo calibration parameters, a calibration image capture sequence acquired snapshots of a four-IR diode calibration board powered using a

9V battery. The four IR diodes were placed in a 150mm square formation. The calibration required the capture (at 0.5Hz intervals) of between 250 and 350 “images” (2D coordinates of the IR diodes in the camera image plane) of the stationary calibration board in a range of orientations, distances and positions across the image. A subroutine was implemented which, due to the passive nature of the markers, was required to ensure IR source identification and point correspondence between camera images. The subroutine calculated the mean X (horizontal) and Y (vertical) pixel coordinates of the four IR diodes over the calibration capture sequence. Depending on their average position in the image (bottom left, bottom right, top left and top right), each IR source was assigned an identifier which was used to pair IR diodes between cameras and their known X and Y coordinates on the calibration board. Because the routine used a planar calibration board, the known Z-axis coordinates were set to zero. A stereo calibration optimisation routine (Bouget, 1999) was used to determine the relative translation and rotation of the cameras in both camera reference frames.

3.4 Calibrated accuracy

The motion tracking system’s accuracy was assessed by placing two IR diodes of known pitch (100mm) on a ‘wand’ which could be readily moved within the operating volume of the WiiMote system. A series of 675 images were captured of the test wand at 5Hz in a range of orientations and positions within the operating volume. Care was taken to avoid losing the IR diodes from either of the camera images. Using the camera parameters determined from the calibration, the 3D positions of the IR diodes were calculated retrospectively and the 3D distance between the IR diodes on the wand was calculated. For all data points, the deviation from 100mm was calculated and the range of errors is represented in Figure 14. With reference to the wand measurement pitch of 100mm, the mean error was 0.69mm (SD 0.33mm) representing a mean percentage error of 0.69%

(SD 0.33%). The volume subtended by the wand during the measurement period was calculated at $0.01m^3$ (equivalent to a cube measuring 215mm along its edges) with an IR diode movement range of 255mm, 122mm and 322mm in the horizontal, vertical and depth directions respectively.

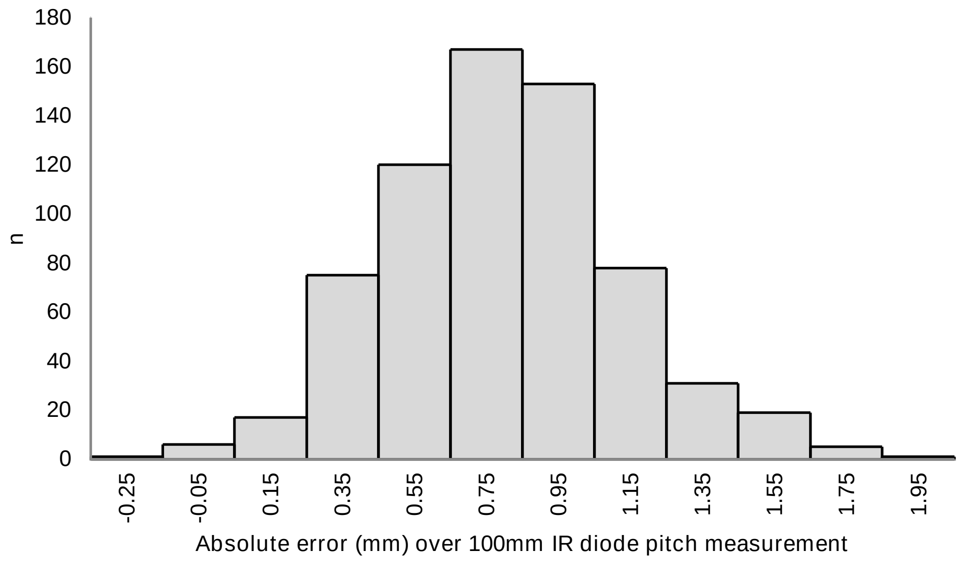


Figure 14. Calibrated system accuracy, histogram of residuals

A histogram of measurement errors of a wand with two IR diodes placed 100mm apart measured over the full measurement volume and a series of 675 images.

3.5 Description of the Postural measurement System

Previous studies have used the Nintendo WiiFit board as a substitute for force platforms in the measurement of postural sway (Clark et al., 2010; Young et al., 2010). As with the WiiMote devices, the WiiFit Board’s wireless Bluetooth connection and battery power made it particularly convenient to use outside the laboratory environment, while its low cost made it amenable to broad scale deployment. The accuracy of the device in comparison to clinical grade force platforms has been demonstrated in adult populations but optimising the signal to noise ratio was required if the system was to be used with children (owing to their low mass).

3.5.1 Mitigating quantization noise effects on postural measures

Data collection (Schmid et al., 2002) and biomechanical (Chiari et al., 2002) parameters have a large influence on spatio-temporal metrics such as CoP excursion velocity (Carpenter et al., 2001; Granat et al., 1990) and frequency-based measures of postural stability (Ruhe et al., 2010). Previous research has highlighted the requirement to standardise data acquisition protocols and filtering methods to facilitate direct between-study comparison of CoP metrics (Ruhe et al., 2010).

Of all standard summary variables that can be generated from CoP movement, CoP path length per unit time was the only one to demonstrate excellent reliability in an analysis of CoP measures to filtering parameters performed by Schmid (2002). In this study, posturographic measures were filtered using a Finite Impulse Response (FIR) filter applied at 0.8 and 10 Hz. The CoP velocity calculated from this signal retained very good reliability across this filtering range, with the Intra-class Correlation Coefficient (ICC) reducing from 0.75 to 0.71 with 0.8 and 10Hz cut-off filters respectively.

What is clear from the review by Ruhe (2010) and earlier studies such as the ones by Schmid (2002) and Chiari (2002) is that there is no standardised acquisition setup that affords reliability and sensitivity across the broad range of metrics that can be derived from CoP behaviour. Integrative measures such as the area subtended by the CoP over the sample time are relatively resistant to acquisition parameters, while measures comprising a derivative component, while sensitive to those parameters, demonstrate good reliability (Schmid et al., 2002).

The aim of this study was not to draw comparisons between postural movement parameters reported in the literature for children and adults, but rather to develop a system capable of reliable interpretation of postural data, while facilitating between-group comparisons. For this reason, sensitivity to collection parameters was less important, but every effort had to be made to limit the effect of anthropometric parameters on measured postural values (Chiari et al., 2002). Sensitivity of postural measures to these parameters could be predicted in a developing population (i.e. children) and would likely be exacerbated for two reasons. Firstly, anthropometric and size variability of the participants will be very much greater across the developmental age range. Secondly, the low mass of the participants in comparison to adult studies might result in the signal comprising a greater ratio of quantisation noise to postural sway signal with a corresponding influence on the CoP metrics used to quantify postural measurement (Granat et al., 1990). Thus, it is particularly important to limit the confounding effect of mass-dependant quantization noise on signal acquisition and limit its effect on the spatio-temporal measures of CoP behaviour, if between-group differences in CoP behaviour in a developing population are to be interpreted correctly.

3.5.2 Filter design

In order to limit the confounding signal/noise effects on CoP metrics, a wavelet filter was applied, as this could effectively exploit the characteristics of Gaussian White Noise (GWN) to determine a noise-related threshold to be applied by the filter for a given participant mass. Using this filtering method, it was possible to attenuate the effects of the quantization noise specific to each participant, enhancing the postural signal remaining. Across the mass range of the participants to be tested (6 - 40kg), six equally-distributed dead-weight recordings of sample length equivalent to the trial length were taken (30s at 60Hz = 1800 samples). The Standard Deviation of the Gaussian White Noise (SDGWN) was calculated on the X and Y channels of the CoP data for each mass sample. An inverse exponential function was fitted to the mass/SDGWN curve on each axis resulting in an r^2 coefficient of 0.998 and 0.999 in the X and Y axis respectively. The function derived for each axis could then be used to calculate the SDGWN for a participant-specific mass, recorded during testing in quiet stance. The calculated value for the SDGWN for the individual was then used to determine the axis-specific wavelet threshold (T) using equation (3):

$$T_{x,y} = \sigma_{x,y}\sqrt{2.\log(n)} \qquad (3)$$

where n is the number of recorded dead-weight samples and σ is the axis-specific standard deviation of the noise signal. For each axis, the wavelet filter was applied with the relevant axial threshold value. The filter applied was a hard-thresholding, non-invariant, Symmlet 4 mother wavelet filter design with a low-frequency cut-off level of 4Hz (Donoho et al., 1999).

3.5.3 Calculation of standard CoP metrics

The length of the path subtended by the CoP was used as a simple, objective measure of postural stability. When comparing populations with significantly different masses, a problem arises in considering the dynamic effects of the mass of the participants on the speed and overall extent of the movement. That is, the CoM of a larger participant will possess a greater amount of inertia. Small fluctuations required to stabilise the CoM will therefore have a minimal effect on the CoM displacement. When measuring at the CoP, this will be observed as a reduction in the path length of the CoM displacement, but interpretation of the effect of mass on path length is conjecture without a dynamical model linking the kinetics of the CoM to the observed CoP behaviour. For meaningful between-group comparisons of postural stability, a measure robust to the effect of mass on CoP displacement is required. The area subtended by the CoP over the test time course could provide a measure which represents the containment of the CoP within a stability region, typically represented by a best-fit circle or ellipse about the 2D dataset. Postural stability is therefore a function of the areas calculated from these geometries, with a smaller area of best fit being associated with more efficient management of the CoM position. Thus, the sensitivity of the metrics to measurement anomalies is reduced by fitting the ellipse or circle to the data falling within the 95% Confidence Interval (CI).

3.6 Experimental validation methods

3.6.1 Participants

Two hundred and sixty nine children were recruited from two local primary schools. The demographic information is presented in table 7.

Table 7. Demographic of test population

	Nursery/ Reception	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6
n	77	46	42	69	44	40	28
Min Age (Years)	3.2	5.9	6.9	7.8	8.9	9.9	10.9
Max Age (Years)	5.8	6.8	7.8	8.8	9.8	10.8	11.8
Mean Age (Years)	5.1	6.4	7.4	8.3	9.3	10.4	11.5
Male	41	20	24	34	22	19	9
Right Handed	67	36	38	64	37	36	26

3.6.2 Procedure

Participants were asked to stand on the WiiFit board, with their feet a shoulder width apart. On verbal confirmation that the participant was comfortable, the participant was instructed to close their eyes, and as soon as the participant had closed their eyes data collection commenced. The experimenter checked that the participant’s eyes were closed throughout the test. Two tests were carried out on each participant: 30s of quiet standing posture with eyes closed, followed by 30s quiet standing posture with eyes open. In the eyes open condition the participant was instructed to fix their gaze on a target placed on the WiiMote board at eye-level. The WiiMote board tripod was adjusted individually for the height of each individual such that the IR source was at the centre of each camera image (1m from the front of the board).

To quantify the relative sensitivity of the rotational movement versus positional movement in describing head movement during quiet standing, the system synchronously collected data using the IR point source system and a three DoF orientation tracker (MTx, XSens, Netherlands). The XSens device was mounted to a stiff, lightweight, adjustable brace strapped to the head of the participant with the single IR point source fixed directly to the XSens device. The XSens device recorded static (angular position) and dynamic (rate of turn, acceleration) information in the three orthogonal axes of rotation which are measured. Movement data was acquired at 100Hz and 70Hz for the XSens device and the Nintendo devices respectively for the duration of the test (Figure 9). The summed angular rotation about all three axes measured by the XSens was the output metric for angular motion of the head. WiiMote position data were post-processed using the pre-determined camera calibration matrices to stereo-triangulate the IR point source position. The output metric from the motion capture system was then calculated as the cumulative path length of the IR diode over the time course of each trial. Raw head rotation (XSens) and position (WiiMote) data were filtered using a 10Hz dual pass Butterworth filter before calculating the output metrics. WiiFit board data were filtered using the Wavelet filtering method discussed previously prior to calculation of the balance metrics.

The output metric from the motion capture system was the cumulative path length of the IR diode over the time course of each trial. The emphasis of the system was simplicity for the user such that the system was usable in-situ by teachers or undergraduate researchers. Marker occlusion is a perennial issue for optical marker systems, and this can lead to significant data loss if the user is unaware of the problem. To minimise this issue whilst maintaining simplicity for the user, a single marker was placed at the highest point on the head avoiding occlusion from narrow camera FOV, narrow IR point source FOV, excessive head movement and the participant's hair/clothing. Following each trial, the system checked connections to the equipment and the quality of the data acquired and highlighted (a) failed connections to any device or (b) no IR point data from either of the cameras or (c) if more than 10% of the data over the course of the trial was "missing data" from either camera. Tests were repeated if one or more of the following occurred: (i) more than one IR point source was detected by the camera (errant IR sources detected, sunlight in camera field of view (ii) IR point source was missing in at least one camera for more than 10% test duration; (iii) failure to acquire XSens or balance board information; (iv) the participant did not follow the instruction to stand as still as possible. Approximately 3% of all trials were repeated because the above criteria were met.

3.6.3 Results

A reliable effect of viewing condition and a reliable effect of age was expected (under the assumption that movements of the head are related to postural stability). Head movement data collected with the XSens yielded no reliable effect of viewing condition (F (1, 303) = 1.881, p = .17, $\eta^2_{p\,=}$ .006) but there was the expected effect of age group (F (6, 303) = 18.694, p < .001, $\eta^2_{p\,=}$ .27). Thus, the XSens was capturing the changes associated with age but lacked the sensitivity to detect the differences between eyes open and eyes closed. Head movement data collected on using the system developed in this study yielded a reliable effect of age (F (6, 311) = 35.518, p < .001, $\eta^2_{p\,=}$ .41) and viewing condition (F (1, 303) = 161.044, p < .001, $\eta^2_{p\,=}$ .34). These results show that this system is capable of producing sensitive data that capture postural effects well established in the research literature. It appears that the low-cost spatial measurement system has advantages for measuring head movements over the expensive inertial sensor system (as hypothesised a priori on the basis that the inertial sensor needs to detect the small angular changes associated with rotations around the ankles, whereas this system measured positional changes) (Figure 15).

When analysing the postural (CoP) data, a reliable effect of viewing condition and age was anticipated. A reliable effect of age (F (6, 309) = 11.461, $p < .001$, $\eta^2_{p\,=}$ .18) and viewing condition (F (1, 309) = 171.288, $p < .001$, $\eta^2_{p\,=}$ .36) was found for the total CoP path length (Figure 15). Likewise, a reliable effect of age (F (6, 298) = 8.549, $p < .001$, $\eta^2_{p\,=}$ .15) and viewing condition (F (1, 298) = 17.698, $p < .001$, $\eta^2_{p\,=}$ .06) was found for the 95% CI ellipse area. It is possible to explore postural sway across the two orthogonal axes using the WiiFit board. Human posture is known to be more stable in the medial-lateral plane than the anterior-posterior plane under normal standing stance (Winter et al., 1996); therefore, higher levels of sway in the anterior-posterior plane could be predicted along with an increased effect of viewing condition in the AP axis. Figure 15 shows that these expectations were met. A reliable effect of age (F (6, 307) = 7.947, $p < .001$, $\eta^2_{p\,=}$ .14) and viewing condition (F (1, 307) = 27.035, $p < .001$, $\eta^2_{p\,=}$ .08) was found in CoP deviation in the medial-lateral plane. The reliable effect of age (F (6, 306) = 14.904, $p < .001$, $\eta^2_{p\,=}$ .23) and viewing condition (F (1, 306) = 288.055, $p < .001$, $\eta^2_{p\,=}$ .49) was also found for the anterior-posterior plane but it can be seen that the effect size for detecting differences in age and viewing condition was larger for the anterior-posterior plane. There were no reliable interactions observed.

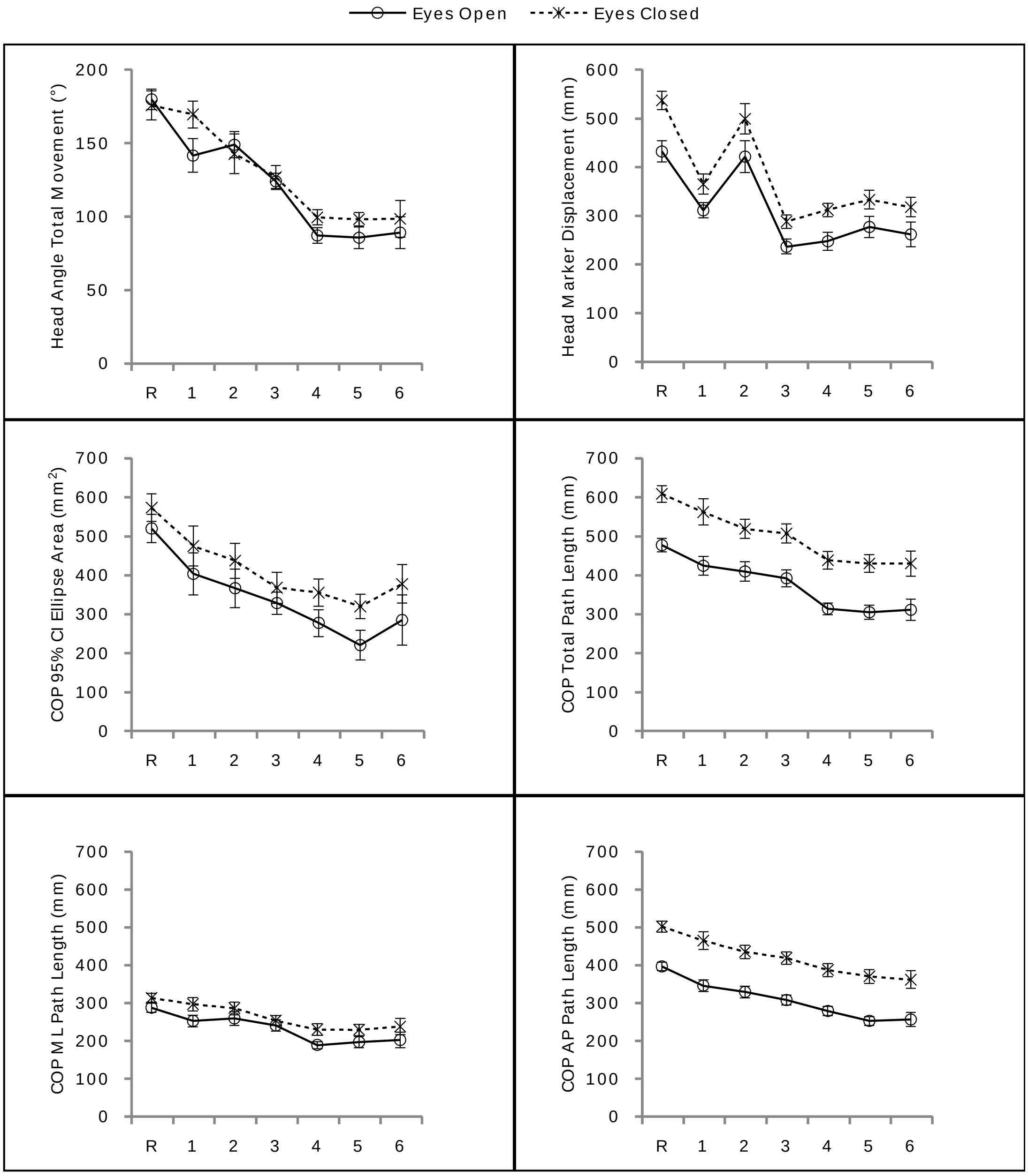


Figure 15. Postural sway results as a function of year group.

Group demographics are detailed in table 7 and all charts represent data collected over a 30s trial duration. Upper left panel: Total head movement defined as the sum of angular rotation about all three principle axes as measured by the XSens device. Shown as a function of age and vision condition. Upper right panel: Total path length subtended by the head IR diode shown as a function of age and vision condition. Middle left panel: 95% CI area of CoP data shown as a function of age and vision condition. Middle right panel: Total path length subtended by the CoP as a function of age and vision condition. Bottom left panel: Total deviation of the CoP in the medial-lateral direction shown as a function of age and vision condition. Bottom right panel: Total deviation of the CoP in the anterior-posterior direction shown as a function of age and vision condition.

3.7 Discussion

A system capable of quantifying postural sway in large numbers of children using widely available and low cost consumer electronics was developed. The postural sway of a large number of children was measured to test the practicality and sensitivity of the developed system. The system generated data of sufficient fidelity to detect the known variations in postural behaviour which occur over the developmental age range and also when the eyes are closed. In addition, the head movements measured with the new method were compared with results generated by expensive inertial sensors, demonstrating that the low cost positional system provided more useful data.

A range of measures based on the behaviour of the CoP were capable of reliably detecting age and vision effects. Similarly, the motion capture system and the single point translation measure were able to detect reliable differences between participants and viewing conditions. The XSens device detected reliable reductions in head movement as a function of age but was not able to reliably distinguish a reduction in head movement when visual feedback was present. This confirmed one of the original predictions that rotational measures of head movement would not be sufficiently sensitive to identify subtle differences in quiet stance behaviours (due to the small rotations that occur at the head in quiet stance). These data therefore suggest that point translation at the head is a more sensitive measure of sway than rotations.

In this study, analysis of the translation of a single point on the head was chosen for two reasons. The first is that a translation of the head yields a translation in the CoM with a resultant deviation of the CoP. Planar deviations in head displacement (broadly occurring in the transverse plane) can be considered analogous to CoP displacement, in that both describe displacement of a single point in the transverse plane. Any similarities, or differences between the magnitudes of both measures can then be used to probe strategic differences in postural management. Second, the addition of three markers to generate a reference frame with six degrees of freedom is not suitable for a largely static task where nominal rotations are anticipated. Moreover, it is easier to monitor the position of a single point of IR light as marker occlusions are very much easier to manage. Nevertheless, this system would not work well in tasks requiring large head rotations.

CoP velocity (CoP path length per unit time) is most effective for a 30s trial duration, with reliability obtained from a single trial (Le Clair and Riach, 1996). However, CoP path length measures are known to be susceptible to quantization noise effects and hence are sensitive to sampling frequency and filtering methods (Granat et al., 1990; Schmid et al., 2002). The results show the quantization noise effects can be controlled with suitable filtering. It was possible to validate the original prediction that the CoP measures would be most sensitive in the anterior-posterior direction. The 95% CI area measure proved to be a robust measure of postural stability, demonstrating that the equipment resolution is sufficient to distinguish the overall movement extents, even where the extent of CoP motion is very small.

Crucially, the nature of the equipment used in the study makes it easily transportable, which is perfect for use across different locations (not just in the laboratory). Its compact size does not require a very large testing area to be available, again making it ideal for mobile usage. It was shown that the equipment can easily be taken to test children in settings such as schools and so could be used as a screening tool to detect developmental disorders effecting postural stability, such as DCD (Tsai et al., 2008). Taking the equipment to children has the benefit of testing them in a familiar, non-intimidating environment, and also means that children do not need to be transported to the laboratory. Because the test is fairly quick and simple to administer, many children can be tested in one session causing minimal disruption to their day.

A low cost system capable of capturing head, hand and centre of pressure data simultaneously was created. The system was deployed successfully in two schools with no problems. The children were happy to wear the head mounted systems and all stood and closed their eyes as instructed. The system was run by undergraduate students following brief training. Thus, the system can be readily used in school settings by non-specialist personnel (which could easily include the teaching staff within a school). The significant differences found between age groups suggest the equipment is sensitive enough to detect subtle changes in postural stability. As well as being a useful tool to study postural development, the measurement system used in the experiment could potentially be used as a diagnostic tool to identify and track children with developmental difficulties (such as DCD).

Chapter 4: Children's seated postural stability as a function of task demands

Overview

Chapter 3 describes the development of a low-cost, portable motion capture system which is capable of detecting subtle effects of vision on posture in children. The present chapter uses this technology but extends its utility by incorporating three sensors at the head, and implementing the synchronous fine and gross (postural) motor measures used in chapters 1 and 2 respectively. In doing so, task-specific postural control can be assessed with due consideration for the head movements such tasks induce. The equipment was adapted for use in the assessment of postural control in the assessment of seated posture to demonstrate its utility in assessing posture in an ecologically valid scenario.

4.1 Introduction

The human nervous system requires a stable base in order to foster the development of accuracy and precision in manual control tasks (Colangelo, 1993; Bertenthal and Von Hofsten, 1998). Instability in posture has consequences for manual control (e.g. unpredictable, irreproducible and inconsistent movements) (Thelen and Spencer, 1998). In contrast, a stable postural base allows for the accurate execution of planned movements, which results in more predictable outcomes and thus allows the acquisition of a motor command repertoire that can be used for skilful interactions with the environment (Burdet et al., 2006). The difficulty for the developing system is that stable posture is disrupted by arm movements. This is because the momentum elicited by arm acceleration result in the destabilisation of the CoM and this perturbs postural control (Pozzo et al., 2001; Shadmehr and Mussa-Ivaldi, 1994; Patla et al., 2002; Harbourne et al., 2013).

Maintenance of postural stability when engaged in a task requiring manual dexterity is often conceptualised as a ‘dual-task’ issue (Huang & Mercer, 2001; Remaud, Boyas, Caron & Bilodeau, 2012; Van Impe, Bruijn et al. 2012; Weeks, Forget et al., 2003). It is consistently found that posture is less stable when a concurrent manual control task is undertaken, implying that the nervous system has limited resources at its disposal which must be distributed appropriately between competing task demands (i.e. maintaining balance and performing the manual task). The capacity limited resources are most stretched when a manual task requires high levels of accuracy and precision. Nevertheless, Haddad et al. (2010) found that young adults were able to increase their postural stability appropriately as the demands of a manual task increased (posting an object through an aperture of decreasing size). In contrast to young adults, children and older adults are less able to cope with ‘dual-task’ demands as postural control is more effortful and less automated in these age groups (Haddad et al. 2013; Yogev-Seligmann, Hausdorff & Giladi, 2008). The progressive refinement of postural control is well-documented across the developmental trajectory from the frequently falling infant to the stable adult (Hatzitaki et al., 2002; Hayes, 1982). Notably, it is consistently reported that there are large differences in postural control between younger and older groups of primary school children (Schmid et al., 2005; Shumway-Cook and Woollacott, 1985; Kirshenbaum et al., 2001).

It is probable that poor postural control in younger children will directly impact on their ability to execute a manual control task (Smith-Zuzovsky and Exner, 2004). Moreover, the perturbations caused by arm movements lead to a conundrum for the maturing nervous system, as a stable base is required when developing manual proficiency (Bertenthal and Von Hofsten, 1998). One simple solution to this conundrum is to sit down. A chair provides postural support and thereby reduces the control demands placed on the nervous system. This is evident in studies which show that the addition of postural support increases movement efficiency, with this effect being most pronounced in younger children (Saavedra et al., 2007; Smith-Zuzovsky and Exner, 2004). For example, reach-to-grasp movements show adult-like levels of proficiency in children when they are seated (Schneiberg et al., 2002). The preceding consideration suggests that the normal disparities in postural stability across age groups may be attenuated when children are seated. This raises the empirical question of whether a standard school chair provides sufficient support to remove the normal differences in stability observed across primary school children. This is an important issue as the majority of fundamental educational skills (e.g. handwriting) are acquired whilst seated at a desk on a standard school chair. This study explored whether sitting children on a standard school chair is sufficient to ameliorate the age differences in postural control ability observed when children are standing. Of particular interest to this study is the extent to which different tasks impact on seated postural stability. The success of the postural system can be measured by the degree to which it allows the successful execution of goal directed actions (Stoffregen et al., 2007; Balasubramaniam et al., 2000; Riley et al., 1999). It follows that the postural control demands are a function of the stability required for the successful execution of a particular task (Stoffregen et al., 2007; Stoffregen et al., 2006; Aruin and Latash, 1996; McNevin and Wulf, 2002).

Seating provides a more biomechanically stable base than a standing bipedal one, for two primary reasons. Firstly the area of the BoS is increased over and above that possible in comparison to the area encompassed by the feet alone (as in bipedal stance). Secondly, the vertical distance between the COM and the BoS is greatly reduced in seated postures. Combining these two factors results in a scenario where it is extremely difficult (in normal static seating while undertaking a tasks such as handwriting) to displace the COM beyond the BoS.

Increasing this biomechanical stability of the individual, it was anticipated that there would be less reliance on anticipatory mechanisms intended to compensate for the destabilising effect of task. Thus, when considering the age-specific patterns of postural management evident in chapter 2, it would be reasonable to hypothesise that, owing to the significantly reduced postural task complexity, these age-dependent effects would be ameliorated. Furthermore, in chapter 2, dynamic instability from the task was countered by postural adjustments which opposed these movements. If postural stability is provided by the chair in the absence of these mechanisms, then it would be reasonable to anticipate an observable effect of more dynamically destabilising tasks such as ballistic aiming movements, where posture would be perturbed as it requires rapid accelerations and decelerations of the arm.

It was hypothesised that the tracing task would require (and allow) minimal postural movement based on the prediction that fine motor control has been shown to require increased postural stability, this mechanism would presumably persist in the seated position as, although greatly reduced, the complexity of the postural task is not absolutely addressed by the addition of seated support.

The effect of the tracking task was not predictable a priori as the postural adjustments will depend on the ability of the children to predict the movement of the target.

As observed in chapter 2, in standing posture there is a tightly coupled relationship between head movement and centre of pressure displacement, so that tasks that require head movements have a destabilising effect on posture. In seated posture there is the possibility that, with an increased level of support offered by increased BoS area the destabilising effect of head movement on the CoP will be reduced.

4.2 Methods

4.2.1 Participants

Three age groups of children were recruited from a primary school in the North of England (30 male, 31 female). Group One (n = 14) had a mean age of 6.2 years (range, 5.8 - 6.8 years), Group Two (n = 25) a mean age of 8.0 years (range, 6.7 - 8.5 years) and Group Three (n = 24) a mean age of 10.1 years (range 9.6 to 10.5 years). None of the children had any history of ophthalmological or neurological deficits and none had any specific learning difficulties (to the best knowledge of the school).

4.2.2 Procedure

Four test stations were set up in a dedicated room provided by the school. Each station was placed in a corner of the room, minimising distractions when concurrently testing multiple participants. The room was artificially lit, with all sources of natural light removed. A plywood board (16mm thick, 1 m^2) was placed on top of a Nintendo WiiFit board to provide a platform for a school chair and table. Spacers were placed under the table’s legs to standardise the height of the chair with respect to the table. The surface of the platform was covered with non-slip floor covering and had a wooden strip added to prevent the chair falling off the platform (Figure 16). For stability the board was rotated 90° clockwise. To reflect this change at the data processing stage, the X and Y axes of the WiiFit board were used as the A/P and M/L direction of CoP movement in the participant’s frame of reference.

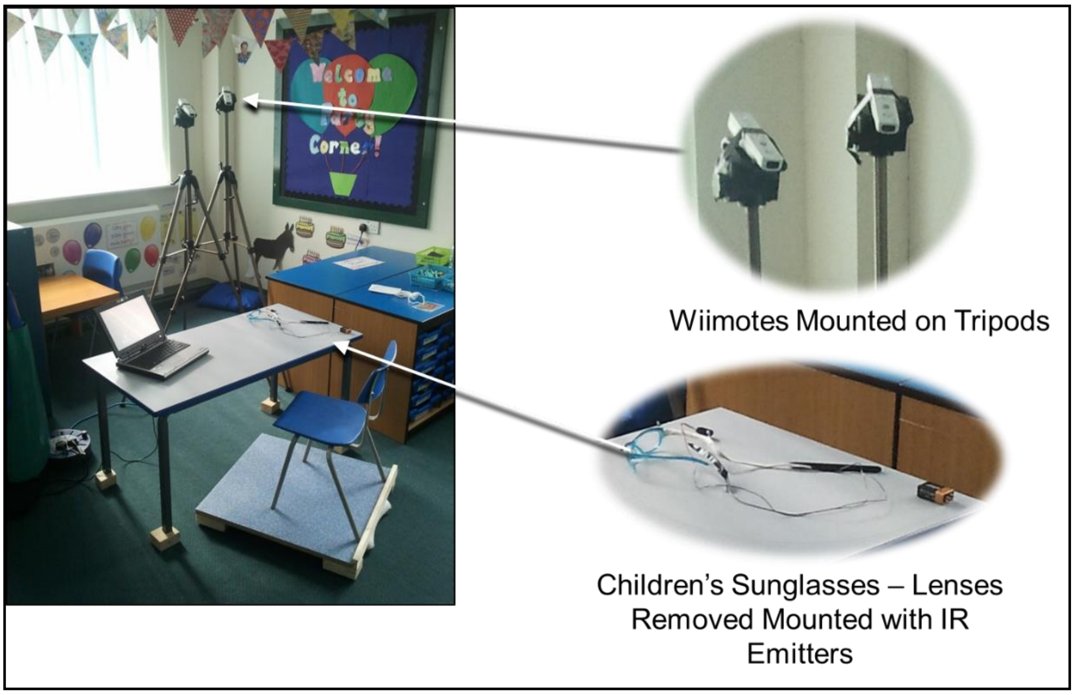


Figure 16. Typical testing station setup

Participants were seated at the table with their feet on the floor and the facing edge of the table in line with the front edge of the seat. In order to capture the rotation and translation of the head, the participants wore spectacles with the lenses removed. The spectacles had three IR diodes forming two orthogonal axes (both origins at the right-hand hinge) extending in the medial-lateral and anterior-posterior direction. Two IR cameras (Nintendo WiiMote) were used to track head movements (Figure 17).

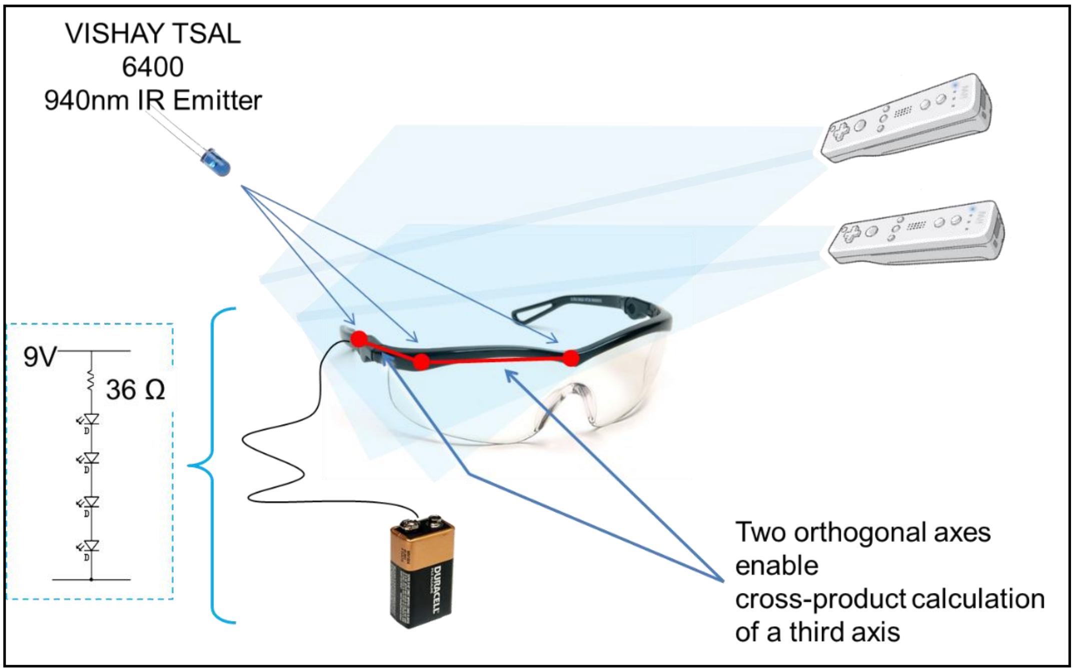


Figure 17. IR emitting glasses construction

The cameras were calibrated by capturing 300 images of a board comprising four diodes, equally spaced in a 150mm square configuration (Figure 18, Figure 19). The calibration procedure (identical to that described in chapter 3) was repeated three times for each station (to ensure that sufficient data were captured to allow for algorithm convergence) and each station was calibrated prior to the morning and the afternoon testing sessions. The total distance subtended by all three diodes during each subtest was used as the absolute measure of head movement.

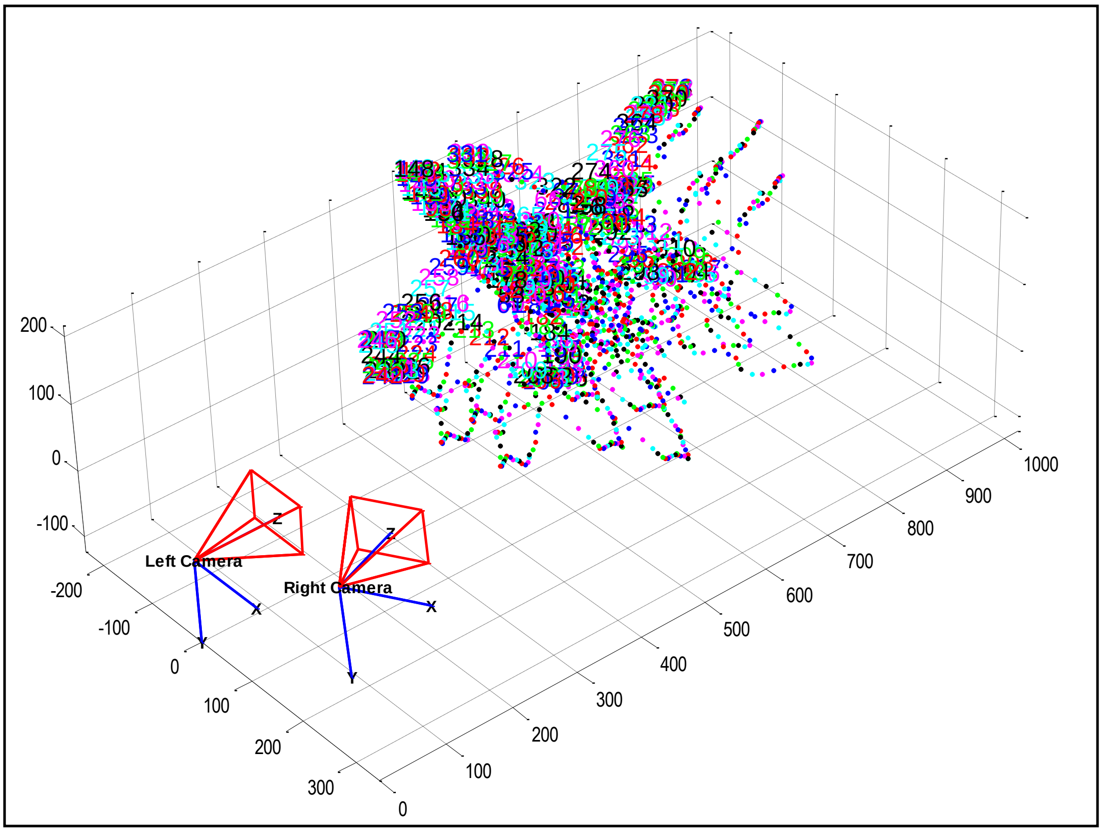


Figure 18. Example calibration result, extrinsic camera properties

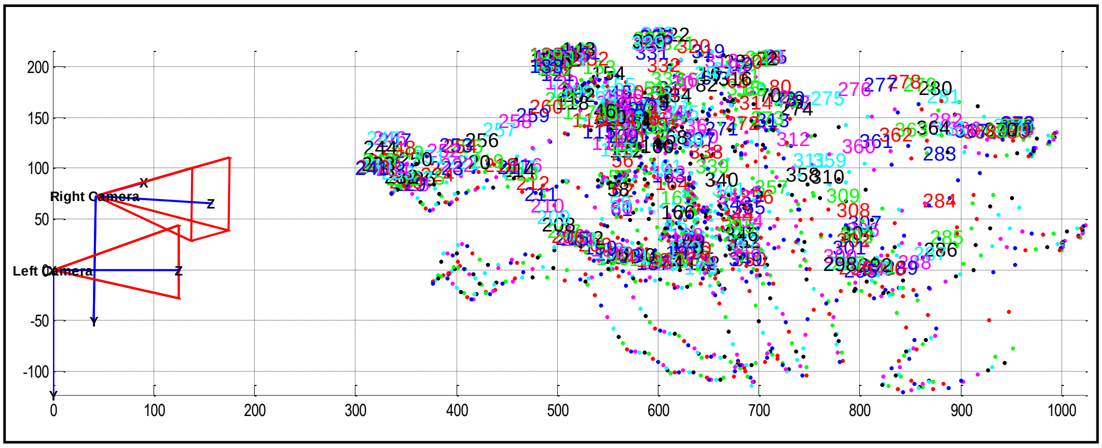


Figure 19. Example calibration result, extrinsic camera properties

In two baseline subtests, participants were asked to sit: (i) with their eyes closed for 30s; (ii) fixate on a cross drawn on white card and mounted on the tripod immediately in front of them for 30s. Participants subsequently completed a battery of motor tasks which included tracking, aiming and tracing subtests. For each test, the tablet’s screen was provided on a horizontal surface (in landscape orientation), which mimics writing with a pen and paper using a pen-like stylus as an input device. The laptop was placed on the table 10 cm from the participant. An on-screen instruction was displayed immediately prior to the start of each subtest.

4.2.2.1 Fine motor control measurement

From filtered time-series of data, a wide variety of spatial, temporal and frequency-based kinematic metrics could then be calculated (see Culmer et al. (2009) for full list). However, to avoid data-mining, only a specific subset of these kinematic variables were chosen to be analysed. These were selected in a principled manner, satisfying the following criteria: (i) variables had to be normally distributed or responsive to transforms that enforced this (e.g. reciprocal, natural log). This legitimated Z-score transformations of such variables, in turn allowing them to be averaged across to give composite scores that indexed overall performance on each subtest. (ii) Variables had to be at least moderately correlated with age ($r > .3$), implying they were a meaningful measures of some characteristic of development in fine-motor control. Thus the following kinematics were analysed as outcomes for the respective CKAT subtests:

For the tracking subtest, the spatio-temporal accuracy of the participant at each sampled time point was measured as the two-dimensional distance from the stylus to the dot centre (i.e. RMSe). Across the data points a mean value for RMSe with respect to the six experimental conditions was calculated (i.e. one per speed [Slow, Medium, and Fast] for both background conditions [without guide-line, with guide-line]). To capture the spatial accuracy of the shape subtended during pursuit, a second metric (Path Accuracy [PA]) was calculated as the mean of the minimum distances from input to the ideal path across all data points (within each condition). Standardised Z-scores were calculated for the spatio-temporal (RMSe) and spatial metrics (PA) within year group for twelve measures (i.e. two metrics, three speeds and two background conditions), after having first applied a reciprocal transform to normalise these outcomes’ distributions. These two metrics were chosen as, in combination, they represent measures which capture a participant's ability to accurately complete the task in the spatial and time domains. Combining these two metrics into a single overall metric, across a range of task difficulties captures a participant's performance. The composite score for tracking was therefore calculated as the arithmetic average of these twelve (standardised) values.

The velocity profiles of skilled aiming movements (defined as those exhibited by healthy adults) typically follow a bell shaped curve, with smooth acceleration and deceleration. A powerful index for classifying movements is the value of their 'smoothness'. The smoothness of the individual aiming movements was calculated using the Normalised Jerk (NJ) index, where jerk is the time derivative of acceleration and is minimised in smooth movements. The jerk measure was normalised with respect to movement time and length and is described in equation (4) (Culmer et al., 2009):

$$Nj = \sqrt{\frac{T^5}{2L^2}\int_0^T j(t)^2 dt} \qquad (4)$$

A maximally smooth 1D trajectory that starts and ends at rest is described by a quarter cycle of a sine wave, which gives a NJ value of 7.75. The metric was extended to 2D by finding the resultant tangential velocity of the movement, and differentiating twice to find the resultant jerk.

Participants were given the instruction to complete each movement "as quickly and as accurately as possible", thus a second measure of optimal task performance would be completing the task (as measured across individual movements) in a short Movement Time (MT). Because these two measured the key performance on aiming movements (with smooth, quick aiming movements being optimal) these metrics were combined to generate an overall aiming movement score. To ensure normality of the distribution of the data generated for these metrics, reciprocal and log transforms were used for values of MT and NJ respectively.

For the aiming subtest, median values for both the reciprocal MT and the log NJ of the aiming movements made within each of the three experimental conditions were calculated separately (i.e. Baseline, Embedded and Jump conditions). These six values were then Z-score standardised within year groups and a composite score for the aiming subtest calculated by averaging these six standardised scores.

For tracing, the minimum 2D distance between the idealised reference path and the stylus was calculated for each sampled time point within a trial. For each of the six trials, the arithmetic mean of these values was taken as a measure of shape reproduction accuracy, termed Path Accuracy (PA). Despite continuous monitoring of the participant by the experimenter, a number of participants were unable to adhere to the instructions to stay within the moving on-screen box with their stylus whilst completing tracing trials. Thus interpretation of participants' accuracy during these trails was potentially confounded, by a lack of standardisation for their speed. Consequently, in order to control for variation in time to complete a trial, a "Penalised Path Accuracy" (pPA) metric was calculated that adjusted PA score with respect to MT. The ideal trial time, including the 1s delay at the onset of the trial, was 36s. To normalise path accuracy in the context of task time, path accuracy was inflated by the percentage participants' actual MT deviated from the ideal 36s value. Standardised Z-scores were calculated for PPA within age group for each shape. A composite performance score for the tracing subtest was calculated as the mean of these values.

Finally, an Overall Battery score for the CKAT was calculated as the arithmetic mean of the respective tracking, aiming and tracing composite scores. This overall score aimed to capture performance across three discrete fine motor tasks, precision movement, ballasting aiming movement and tracking.

4.3 Results

Postural stability outcomes (Head Movement and CoP) at Baseline were summarised as the average of the scores obtained when seated with eyes fixed on a stimulus and eyes closed. Head movement and CoP were analysed separately as dependent variables using full-factorial mixed ANOVAs that specified Age as a 3-level between-subject independent factor (4-5 year; 6-7 years; 8-9 years) and Task as a 5-level within-subject repeated measure (Baseline; Tracking; Tracking with Guide; Aiming; Tracing).

4.3.1 Centre of Pressure

The main effect of Age on CoP (F (2, 55) = .04, p = .847, $\eta^2_{p <}$ .01) and the Age X Task interaction term (F (8, 220) = .72, p = .674, η^2_{p} =.03) were both non-significant. However, there was a significant main effect of Task (F (4, 220) = 17.32, p < .001, $\eta^2_{p =}$ .24, ε = .37). Post-hoc pairwise comparisons, with Bonferroni adjusted alpha, revealed significantly lower CoP displacement for the tracing task (M = -.458, S.E. = .074) relative to all other comparisons (p's < .006). In contrast, aiming CoP displacement (M = .5, S.E. = .112) was significantly higher relative to all other conditions (p's < .044). There were no significant differences (p > .05) between Baseline (M = -.043, S.E. = .161), tracking (M = 0.02, S.E. = 0.91) and tracking with guide (M = .061, S.E. = 0.98). See Figure 20.

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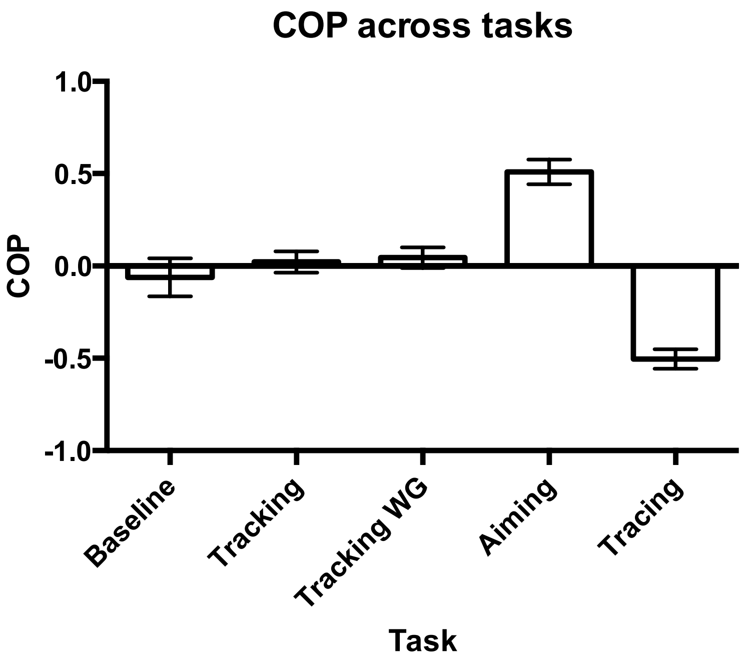

Figure 20. Seated CoP as a function of task shown as Z-scores

No differences were found between Baseline CoP and Tracking and Tracking with Guide tasks. CoP displacement was largest in the aiming task and smallest in the tracing task. Error bars represent ±1 Standard Error of the Mean (SEM), corrected to remove between subject variance (Loftus and Masson, 1994).

4.3.2 Head movement

There was no significant main effect of Age (F (2, 25) = .18, p = .84, η^2_p =.014) and no Age X Task interaction (F (8, 100) = .53, p = .72, $\eta^2_{p\,=}$ .04). However, there was a significant main effect of Task (F (4, 100) = 5.85, p = .005, η^2_p = .19, ε = .15). Post-hoc pairwise comparisons, with Bonferroni adjusted alpha, revealed that for Tracing, head movement (M = -.461, S.E. = .078) was significantly lower than aiming (M = -0.77, S.E. = .137, p = .007), tracking (M = .266, S.E. = .244, p = .046), and Tracking with Guide (M = .129, S.E. = .176, p = .003), but not Baseline (p = 1). There was a trend towards a difference between Tracking with Guide and Baseline which approached significance (p = .087). No other comparisons reached significance (p > .05). See Figure 21.

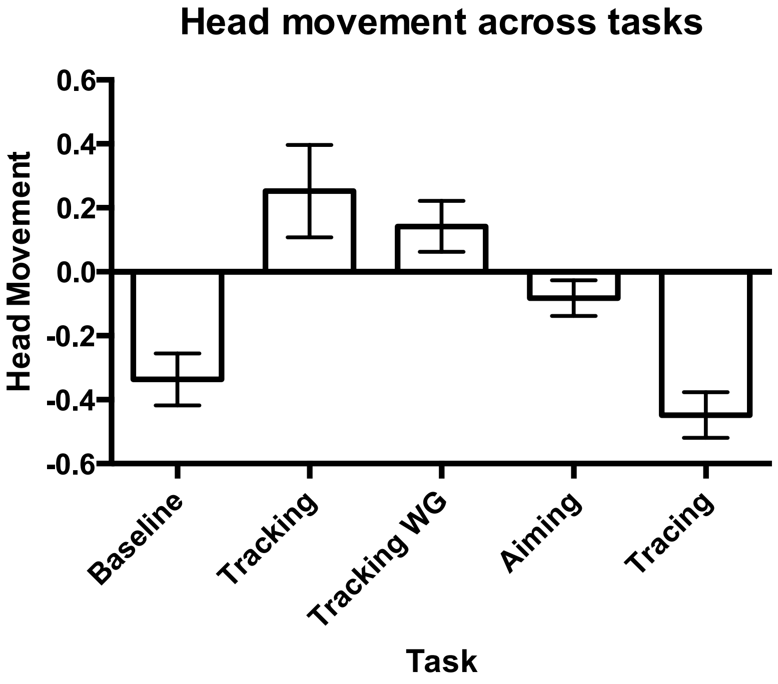

Figure 21. Head movement as a function of task shown as Z-scores

As expected, children displayed a larger amount of head movement for the two tracking tasks. Head movement was lowest during tracing. After application of Bonferroni adjusted alpha, no other comparisons reached significance. Error bars represent ±1 SEM, corrected to remove between subject variance (Loftus and Masson, 1994).

4.3.3 Manual performance

In order to examine if age effects were present in the manual control component of the task, the overall CKAT battery score was specified as a dependent variable and analysed using a one-way ANOVA that used Age as a 3-level between subjects factor (4-5 years; 6-7 years; 8-9 years). A statistically robust main effect of Age was found (F (2, 60) = 37.85, p < .001, η^2_p =.56). Post-hoc pairwise comparisons revealed significant differences in comparisons between each successive age group (p’s < .029). See Figure 22.

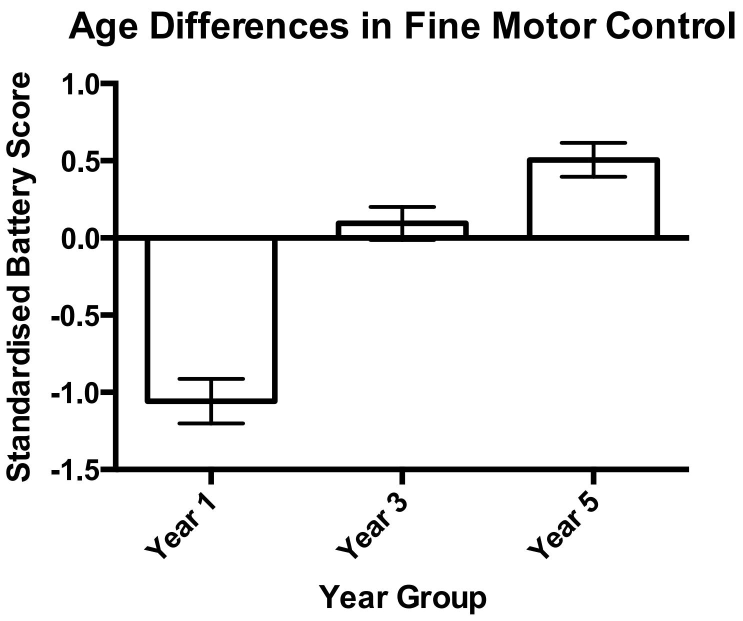

Figure 22. CKAT battery performance Z-scores as a function of age

A significant effect of Age was observed in CKAT battery performance. Children aged between 8-9 years performed significantly better than children aged 6-7 (p = .029) and 4-5 (p < .001). The 6-7 year olds had significantly higher scores than the youngest children (p < .001). Error bars represent ±1 SEM.

4.4 Discussion

This study investigated the role of seating on postural stability with different manual tasks across three age groups of primary school children. The main findings were: (a) seating attenuates the age-related differences in postural control observed in Chapter 2; (b) postural control in seated children is modulated in a principled manner by task demands: stability is increased when tracing, decreased when generating aiming movements and minimally disrupted when a predictably moving target is manually tracked.

Postural stabilisation is necessary to counteract the consequences of arm movements on the CoM (Bernstein, 1967; Von Hofsten, 1993). Clear improvements in postural control as a function of age have been demonstrated in a number of studies (Schmid et al., 2005; Schneiberg et al., 2002; Harbourne et al., 2013; Haddad et al., 2012) and a child's ability to make postural adjustments in anticipation of forthcoming perturbations increases with age (Inglin and Woollacott, 1988; Girolami et al., 2010). In line with this, data in this thesis indicate that predictive postural compensation mechanisms for arm movements develop during childhood. Nevertheless, the present data suggests that the addition of a standard school seat provides enough postural support to attenuate these well-established maturational differences in postural control. It is always difficult to interpret a finding of no significant differences and it is entirely possible that subtle postural differences existed between the age groups that were undetectable owing to lack of power. Nevertheless, this result is in stark contrast to the findings from chapter 2 with similar numbers of children where large differences in postural stability were found. It is thus possible to conclude that the provision of a seat has a profound effect on the size of the postural differences, even if it does not remove them completely.

Seating provides a more biomechanically stable base than a standing bipedal one. The additional postural support provided by a seat reduces the demands placed on the nervous system as the disruption to postural stability from arm movements is minimised. It has been shown previously that the increased postural support afforded by sitting results in a reduction in the magnitude of the usually observed anticipatory postural adjustments made in anticipation of forthcoming CoM displacement (van der Heide et al., 2003). A 9-year-old child has a more developed postural system relative to a 5-year-old, which results in superior performance whilst standing. In this context, proficiency in skilled manual control whilst seated is much less dependent upon the ability to stabilise the CoM in response to perturbations caused by arm movements.

Seated postural control was examined across different manual control tasks and it was hypothesised that different tasks should differentially impact posture. Consistent with a large body of research, it was found that manual tasks modulated postural stability (Aruin and Latash, 1996; Bardy et al., 1999; McNevin and Wulf, 2002; Riley et al., 1999; Stapley et al., 1999). In the tracing task, which required the largest degree of precision, postural CoP displacement and head movement were minimised. This is consistent with research demonstrating the ‘freezing’ of degrees of freedom in the body to maintain stability in tasks that have high accuracy demands (Stoffregen and Pagulayan, 2000; Haddad et al., 2012). In the aiming task, the greatest amount of CoP displacement was found, with reasonable amounts of head movement. This was expected as the dynamic forces generated by the limb during the accelerations and decelerations that occur throughout the task result in a relatively large degree of postural disturbance. This disturbance occurred across all age groups and it indicates that the children were not able to compensate for the displacement of mass caused by the ballistic nature of the arm movement. In the tracking tasks, the target movements were predictable. As such, the tracking task more readily allowed for the planning of postural adjustments (Burdet et al., 2006) and there were no differences in CoP displacement relative to baseline. Previous studies have shown that the speed of the arm movement and the predictability of the task dictate the magnitude of postural adjustments (Horak et al., 1984; Cordo and Nashner, 1982; Crenna et al., 1987). In Chapter 2 it was found that the tracking task had a destabilising effect on posture (possibly mediated by the head movements generated in response to the task demands). The provision of a seat appears to have allowed children to produce the compensatory forces necessary to minimise the perturbations to posture caused by the arm movements (Shadmehr and Brashers-Krug, 1997; Burdet et al., 2006; Krakauer et al., 1999; Kawato, 1999). The tracking task did generate a large amount of head movement relative to the other tasks, as might be expected from the need to maintain fixation on the moving target (as found previously in Chapter 2). The fact that the head movements were not associated with decreased postural stability supports the hypothesis that the synergistic relationship between head movements and posture would be reduced when the children were seated.

A standard school chair was used, and this appeared to provide sufficient support to attenuate the large postural differences normally present in different age groups of primary children. This study has shown that it is possible to ameliorate the differences in postural control through the provision of seating in typically developing children, but a standard school seat might not provide sufficient support for children with movement difficulties. A widely used intervention for children with cerebral palsy is to provide adaptive seating based on biomechanical and neurodevelopmental principles. This is predicated on the principle that improved postural control increases manual control (Chung et al., 2008; Smith-Zuzovsky and Exner, 2004; Case-Smith et al., 1989). This raises the question of whether children with more subtle motor deficits (e.g. DCD) might also benefit from specialised seating.

In the introduction to this chapter it was suggested that childhood development does not follow a linear progression from unskilled to skilled behaviour. The non-linear nature of the developmental progress can be seen within the data collected. For example, in chapter 2, the oldest group of children show clear improvements in their ability to maintain stable posture when visually tracking a target but have almost identical CoP displacement in the manual tracking task. This pattern of results is consistent with the notion that different skills develop at different rates with progression in one skill often dependent on another skill improving first. The synergistic relationship between head, hand and postural control appears to provide a good model of this dynamic interdependency. In fact, the relationship is further complicated by the anatomical changes that occur over the developmental period meaning that the system needs to compensate for changes in mass, lever length, distribution of weight etc. However, this chapter demonstrated that it is not only possible to attenuate age effects through the additional support provided by a chair, but that postural stability is affected by the demands of the task above and beyond postural control development.

Chapter 5: The relationship between postural stability and manual control in children

Overview

Chapters 2 and 4 describe variants of the system developed which are capable of assessing the task-dependent nature of postural movement, with a view to understanding how the postural system compensates for volitional movements. Data Synchronous fine and gross movement measurement afford analysis of the direct, dynamically linked relationship between a suprapostural task and posture. This chapter investigates fine and gross motor control in isolation, and by studying the interrelation between fine and gross motor control processes and how they are linked over development.

5.1 Introduction

Many standardised assessments of childhood motor performance reflect this division in their design and subscales. For example, the Movement ABC-2 comprises of three sets of tasks, each set tailored to assess one of the following ‘sub-components’ of motor-control: ‘Manual Dexterity’, ‘Aiming & Catching’ and ‘Balance’ (Henderson et al., 2007). The justification for compartmentalising motor control performance into these sub-categories is not clear. Henderson and Barnet (1998) state that it follows an “agreed taxonomy” but this agreement is based only on subjective “common sense and clinical experience”. Until recently there has been little empirical evidence to justify assessing motor skills along such lines (Schulz et al., 2011).

One could argue that categorising any action as either ‘fine’ or ‘gross’ is overly simplistic, given that many motor tasks require fine and gross-motor activity in conjunction. From infancy, skilled postural control is a prerequisite for the acquisition of optimal reaching and grasping behaviours (Lobo and Galloway, 2008; De Graaf-Peters et al., 2007). Postural stability moderates the rate at which infants learn successful grasping (Cunha et al., 2013) and reaching is comparatively impaired in infants who have not yet developed the compensatory head and trunk movements required to counterbalance their arm movements during such behaviour (De Graaf-Peters et al., 2007; Ferdjallah et al., 2002; Clark et al., 2010). Even in adulthood, postural stability is found to vary as a function of the level of precision required by a concurrent manual control task (Haddad et al., 2010). Indeed, a primary role of the human postural system appears to be to provide the stability necessary to obtain reliable visual information, which is vital for guiding skilful manual interactions with the world (Fallang et al., 2005; Thelen and Spencer, 1998; Haddad et al., 2013). This view is at the heart of the ‘proximal-distal’ theory of motor development (Wang et al., 2011), which proposes that (proximal) gross-motor skills must be developed first to give a platform for more in-depth exploration of the world via later emerging (distal) fine-motor abilities (Barnhart et al., 2003; Deconinck et al., 2006).

An integrated role for (gross-motor) posture in the function and development of (fine-motor) manual dexterity makes sense from a mechanical perspective. This is illustrated by considering an imminent volitional movement to reach for an object. The postural system generates pre-emptive momentum from displacement of the CoM, opposed in direction and magnitude to the momentum generated by the hand movement. This anticipatory postural adjustment (APA) results in a cancellation of the force generated by the hand movement and minimises the CoM displacement (Massion, 1992). The integration of postural and fine-motor control through APAs becomes more proficient over childhood and allows for the development of increasingly more complex and skilled manual control behaviours (Van Der Fits et al., 1999).

These relationships between postural stability and manual dexterity do not mean that performance within both domains is driven by single underlying factor, however. Children who experience difficulties in motor development often have a deficit in fine but not gross-motor skills and vice versa (Zwicker et al., 2012; Visser, 2003), implying that distinct processes may be responsible for each skill's development. This interpretation agrees: (i) with research that shows gross but not fine-motor skills in infancy are a significant predictor of cognitive performance at school age (Piek et al., 2008) and (ii) reports of both boys and girls showing isolated advantages on specific motor tasks (Junaid and Fellowes, 2006; Thomas and French, 1985; Smith et al., 2012). The independence of gross and fine-motor skill development is further supported by evidence that their trajectories (from infancy to pre-school) are best described by different mathematical models (Darrah et al., 2009). Motor skill development in general follows a nonlinear and discontinuous trajectory (Kuhtz-Buschbeck et al., 1998; Riach and Starkes, 1994), punctuated by the accomplishment of increasingly complex hierarchical 'motor milestones' (WHO, 2006). These milestones present as emergent behaviours generated by a number of interconnected processes - for example over-arm throwing is initially a predominantly upper limb action that matures over time to incorporate more gross-locomotor aspects (e.g. a step phase and rotation of hips, torso and shoulder prior to release) (Malina, 2004). Such an observation implies that postural and fine-motor control may be independent dynamical processes, which in the course of development often create more complex 'higher level' coordinated motor actions.

Studies directly testing the strength of association between children's gross and fine-motor control skills are scarce. Moreover, those that do exist report very mixed findings in generally small sample sizes. In infants, Loria (1980) found no correlation between reaching and prehensile skills in a sample of twelve 30-week old children using objective observational rating methods. Case-Smith, Fisher and

Bauer (1989) measured a sample of 60 children aged between 2 and 6 months old on the Posture and Fine-motor Assessment of Infants (PFMAI) scale and found scores for posture only accounted for 12% of the variance in fine-motor control scores. In contrast, Wang et al. (2011) found that in a sample of 105 6 to 12 month old pre-term infants, postural control assessed using the Alberta Infant Motor Scale was a significant predictor uniquely explaining 25% of the variance in fine-motor control, assessed using subtests from the Peabody Developmental Motor Scales. Beyond infancy, Rosenblum and Josman (2003) examined fine-motor performance using a peg-board manual-dexterity task and a set of balance tasks from the Bruininks-Oseretsky Test of Motor Proficiency (BOTMP), in 47 5 year old children. They found small-to-moderately sized correlations between some of the fine-motor and postural-stability outcomes (ranging from r = -.31 to -47) but these results were affected by ceiling effects on some measures and statistical analysis did not adjust for multiple comparisons. Two studies have looked for relationships between proximal muscle activation (underpinning posture) using electromyography and performance levels on pencil-paper handwriting and drawing tasks: Wilson and Trombly (1984) showed no relationship between magnitude of (gross-motor) muscle activation and quality of performance on two standardised assessments of fine-motor control in a sample of 16 6 to 8 year olds. In contrast, Naider-Steinhart and Katz-Leurer (2007), found that decreased variability in both proximal (trapezius) and distal (thumb) muscle activity were associated with faster handwriting-speeds in a sample of thirty-five 8 to 10 year olds.

Given the contradictory and often methodologically limited extant research it is necessary to obtain new empirical data to better understand the relationship between gross and fine-motor skills (in particular between postural stability and manual dexterity). Is it more appropriate to view these skills as: (i) completely independent and requiring absolute taxonomic separation (Henderson and Barnett, 1998); (ii) highly correlated attributes that reflect an underlying ability (a postulated ‘motor ability’ construct); or (iii) separate processes that nonetheless combine in a co-dependent manner (Haddad et al., 2013)? It is important to determine which of these the more accurate conception is. This is because it has implications for the structuring of therapeutic and rehabilitative interventions. The existing evidence is often used to argue against the ‘proximal-distal’ theory (Case-Smith et al., 1989; Rosenblum and Josman, 2003), which many occupational therapists use to guide and develop interventions (Wang et al., 2011). It is clearly the case though that a more robust and methodologically rigorous study is required before the validity of such intervention-guiding theories can properly evaluated.

The existing literature has utilised relatively unsophisticated assessments of gross and fine-motor control that are too time consuming to be employed in large population based samples. Furthermore, these tools tend to produce noisy estimates of ability because they rely either on observational judgements, simplistic scoring criteria (e.g. “pass/fail” judgements) and/or require participants to produce unfamiliar behaviours that lack ecological validity (e.g. standing on one-leg for an extended period of time). These issues are particularly problematic if one wants to conduct research in large samples and detect subtle variations in task performance (Culmer et al., 2009). To address these issues, a postural measurement rig was used, capable of providing accurate and reliable quantitative measures of postural behaviour in children across the primary school age range (see chapter 3). In conjunction with this setup, a computerised battery of manual fine-motor control tests, the CKAT system was also used, to provide detailed kinematic investigations of end point control across a range of subtests including tracking, sequential aiming and tracing tasks (Culmer et al., 2009). This software platform has been used previously as a tool for investigating motor-learning and manual control in a number of experiments (Gonzalez et al., 2011; Johnson et al., 2010; Raw et al., 2012a; Raw et al., 2012b). It was reasoned that testing a large number of children on these objective measures of motor control would allow detection of associations between postural stability and manual motor performance.

5.2 Methods

5.2.1 Participants

277 children (male = 133, female = 147; mean age = 7 years, 8 months; range 3 years, 2 months to 11 years, 10 months) were recruited via opportunity sampling from two schools in the West Yorkshire (United Kingdom) region. Ethical approval for this study was obtained from the University of Leeds Ethics and Research committee.

5.2.2 Postural measures

Postural movement was calculated using a custom motion capture rig and force platform, specifically designed to be used in schools described in Chapter 3. The rig comprises a stereo-camera motion capture system which measures the 3D position of an IR diode at 60 Hz. A battery powered IR diode was placed on a light, inflexible plastic brace placed on the child's head, which provided a measure of HR. In addition to the measure of movement at the head, a Nintendo Wii Fit board was used to simultaneously monitor the participant's CoP at 60 Hz.

Participants were asked (i) to stand with their feet shoulder width apart with their eyes closed for 30 s, then (ii) to stand with their feet shoulder width apart with their eyes fixed on a target placed 1 m away at eye level. During both conditions (hereafter referred to as 'Eyes-closed' and 'Eyes-open' respectively) the participants were constantly observed to ensure compliance.

HM data was filtered using a 10Hz dual pass Butterworth filter and the CoP data was filtered using the Wavelet filter described in detail in chapter 3. After filtering, the 3D and 2D path lengths subtended by the IR diode and CoP respectively were calculated (in mm) for each 30s trial.

Allowing time for measurement equipment setup and rest breaks, this session lasted approximately 3 minutes.

5.2.3 Fine-motor control measures

During a separate testing session (on another day at least two days distant from the postural session) participants completed a battery of fine-motor tests using the CKAT system. This was completed as per the test battery described in detail in chapter 1.

5.3 Results

5.3.1 Defining outcome measures

5.3.1.1 Postural Measures

To examine postural control, both HM and CoP variables were analysed separately. A composite measure of these two outcomes, which would be considered an index of overall postural stability, was calculated. Shapiro-Wilks tests indicated normality assumptions were met for HM and CoP measures (*p*'s > .05).Thus, Z-score transformations could be used to convert participants' HM and CoP scores to a unified scale, in turn facilitating a mean of these two scores to be calculated to give a 'Posture Composite' score. In order to control for the well-established age differences in motor control, we experimented with three different approaches to standardising. First, a participant's scores on the gross-motor measures were standardised in relation to mean and standard deviation for their school year within the sample (Years 1, 2, 3, 4, 5 and 6). Second, subjects were separated based on the year of birth and standardised in relation to these group's means and SDs. For this, the following groups were used: 2009-2008; 2007-2006; 2005-2004; 2003-2002 & 2001-2000. Finally, scores were standardised relative to the entire sample and age included as a covariate in subsequent statistical analysis. Irrespective of approach the same pattern of results was observed during analysis, demonstrating the robustness of these results. Therefore, for the sake of conciseness, from here on we report results in which Z-scores were calculated based on the first approach described only.

5.3.1.2 Fine-motor control measures

A series of summary, standardised metrics were generated as described in detail in section 4.2.2.1., along with an overall CKAT (fine motor) performance score.

5.3.2 Statistical Analyses

To begin exploration of relationships between gross and fine-motor control, a total of nine Pearson's correlations were computed. Performance on the HM, CoP and the Postural Composite outcome measures, respectively, were correlated against the CKAT overall battery score. Separate analyses of when subjects had their eyes open and eyes closed were conducted, as well as analyses of average performance across these two conditions. These data (see table 8) show significant correlations for each metric (r's > -.14; *p*'s < .022). On the two posture conditions posture independently, the strongest correlation with CKAT score was observed for head movement during the eyes open condition (r = -.26 (277), *p* < .0001). In the most reductive contrast (i.e. one overall score for posture versus one overall score for fine-motor control), the postural composite score showed a significant correlation with fine-motor control battery score (r = -.268 (277), *p* < .0001). These negative correlations indicated that as performance on the CKAT battery improved (higher score) postural instability fell (i.e. lower HM, CoP and Postural Composite scores fell).

Table 8. Correlations between overall CKAT battery score and measures of postural stability, across eyes-open and eyes-closed conditions and a mean average of both conditions

Postural Measure	r	*p*	t
Eyes-closed Condition			
Head Movement	-.282	<.001	-4.83
Centre of Pressure	-.141	.022	-2.30
Postural Composite	-.240	<.001	-4.14
Eyes-open Condition			
Head Movement	-.263	<.001	-4.54
Centre of Pressure	-.171	.005	-.288
Postural Composite	-.242	<.001	-4.15
Mean-average of both conditions			
Head Movement	-.288	<.001	-5.00
Centre of Pressure	-.177	.003	-2.99
Postural Composite	-.268	<.001	-4.62

Linear regression analysis was conducted to determine if from postural stability scores significantly predicted fine-motor control performance. The postural composite score was used as the predictor variable and the overall CKAT battery score was used as the outcome variable for the linear regression model. A scatter plot of the data indicated that the assumption of linearity was reasonable, whilst the cumulative distributions plot of the standardised residuals in Figure 23a supported the assumption of normality. Plotting the residuals against the fitted values (Figure 24b) suggested no violation of the assumption of constant variance of the random errors.

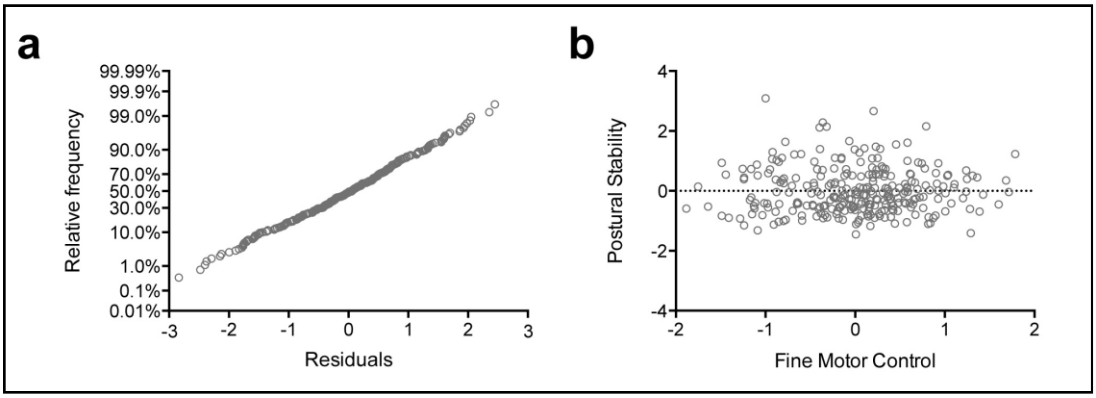

Figure 23. Model residuals against fitted values for postural and fine-motor scores

a) Cumulative distributions of the standardised residuals in the model plotted on the probability axis indicate normality; b) Residuals plotted against fitted values for the linear regression model

Results of the linear regression model (Table 9) indicate that fine-motor control could significantly be predicted from children's gross-motor aptitude (b = -0.24, β = -0.27, t(277) = -4.62, *p* <.001).

Table 9. Linear regression model, fine and gross-motor performance

Predictor variable	b	Standard Error	β	t	*p*
Constant	0.01	0.04		0.28	0.78
Posture composite	-0.24	0.05	-0.27	-4.62	< .001

Specifically, the composite measure of postural stability explained a modest but significant proportion of variance in fine-motor manual control (7%), as indexed by the overall CKAT battery score ($r^2 = .07$, F(1, 277) = 21.37, *p* < .001). See Figure 24 for the linear regression plot.

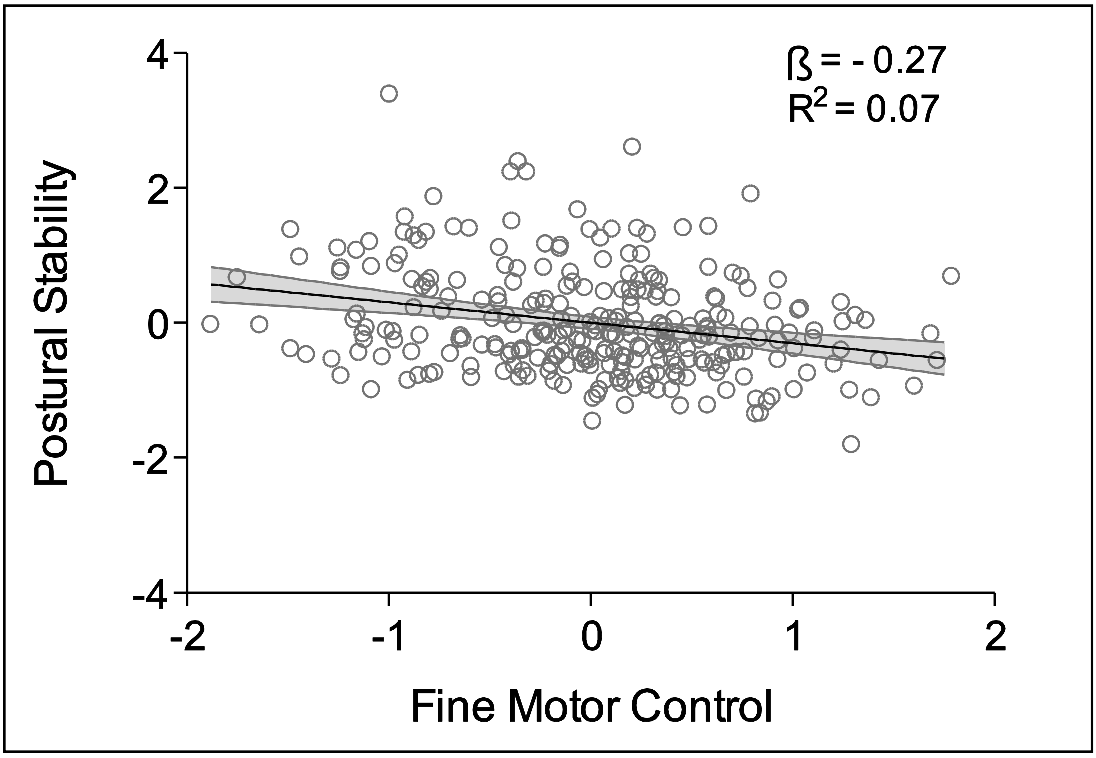

Figure 24. Linear regression plot between fine and gross-motor control Z-scores

Linear regression analysis indicate that gross-motor aptitude could predict fine-motor control performance (b = -0.24, β = -0.27, t(277) = -4.62, *p* <.001), with the predictor variable able to explain 7% of the total variation in fine-motor control performance (r^2 = .07, F(1, 277) = 21.37, *p* < .001). Shaded area represents 95% confidence interval of the regression line. Abscissa shows standardised fine-motor control performance, as indexed by CKAT battery performance, and ordinate represents standardised scores on the composite measure of postural control.

5.4 Discussion

Is it possible to predict performance on a battery of fine-motor (manual) tasks from gross-motor performance (postural stability)? It is not possible to answer this question a priori. On the one hand, it is well established that separate neural systems underpin postural control and manual dexterity, suggesting that measures of performance will be independent (Malina, 2004). On the other hand, there are reasons to suppose that these different skills might have a correlational relationship. Studies on infant development indicate that adequate postural control is a prerequisite for the development of skilled upper-limb actions e.g. optimal reach-and-grasp behaviour (Lobo and Galloway, 2008; De Graaf-Peters et al., 2007). These developmental studies indicate co-dependency between posture and manual control and such dependencies might give rise to a correlation between measures on tasks that tap into these abilities. Nevertheless, in infancy posture and manual control follow nonlinear developmental trajectories with discontinuous progression between discrete developmental stages in both the mastery of upright stance and manual control (Kuhtz-Buschbeck et al., 1998; Riach and Starkes, 1994). Furthermore, the rate of development of these systems appears to differ according to sex (Thomas and French, 1985; Smith et al., 2012; Junaid and Fellowes, 2006) suggesting an independently developing set of processes. It can be seen that empirical data are required to resolve the question of the correlational relationship between measures of postural stability and manual skill.

Previous research seeking to examine the relationship between postural stability and manual skill has produced unclear results (Loria, 1980; Case-Smith et al., 1989; Wang et al., 2011; Rosenblum and Josman, 2003). This is perhaps unsurprising when one considers that extant studies have collected data from relatively small populations and relied on subjective measures. To address these issues, the present study used objective measures of postural stability and manual dexterity and collected data from a reasonably large population of school children. The results showed a significant but small relationship between standardised scores on each task. Specifically, postural stability was able to predict 7% of the variance in fine-motor control performance. This allows rejection of the hypothesis that these skills are completely independent. Importantly, the measures were taken at different time points (separated by two days). This arrangement provides a strong test of the hypothesis that the different skill measures will have a correlational relationship. Nevertheless, the majority of the variance was not explained, thereby allowing rejection of the hypothesis that a single attribute (a postulated ‘motor ability’ construct) underpins gross and fine-motor control. The picture that emerges is one where the development of posture and manual control are largely separate but nonetheless have a degree of co-dependency. The interactions between reaching for an object and postural maintenance have been described previously in the context of dynamic systems theory, where development is characterised by evolving and dissolving patterns of dynamic stability, as opposed to a set of linear progressions towards mature behaviour (Fallang et al., 2005; Thelen and Spencer, 1998; Haddad et al., 2013). In this formulation, postural and fine-motor control mechanisms can be viewed as independent dynamical processes, which often interact in the course of development. These interactions are marked by the emergence of more complex 'higher level' coordinated motor actions. This conception is consistent with longitudinal studies of development and appears to capture the findings of the present study in an elegant manner.

The dependency between posture and manual control is most evident in cases of abnormal development (e.g. cerebral palsy) where an inability to obtain stable posture prevents the acquisition of manual skill. In this context, a failure to reach a fundamental 'motor milestone' produces an impasse for the manual control system. These gross failures might produce a binary outcome where postural stability is either sufficient or insufficient to allow normal manual control to develop. The weak relationship found in the current study suggests that the level of manual skill reached is largely independent of postural skill level once a basic level of postural stability has been reached - at least in the age range of children tested in this study. A developmental divergence hypothesis might suggest that testing younger children than those included in this sample would yield stronger relationships. Indeed, the strongest evidence for such a relationship in the earlier literature has been in research conducted on infants (Wang et al., 2011). Nonetheless, the present study shows that the relationship between postural skill and manual ability is weak above the age of three years. It seems reasonable to suggest that manual skill can develop despite poor postural skills if external objects are used to stabilise posture. For example, once a child is able to sit on a chair they can use the stability of the chair to reduce the postural control demands (ref. Chapter 4, e.g. children learn to write whilst seated at a desk).

In chapter 2 it was found that there exists a functional relationship between the task performed and how postural control was managed in the context of this task. The ability to adequately compensate for a dynamically destabilising task develops over time. Therefore, when the youngest children are asked to perform a demanding task with their hands, their posture is significantly more destabilised than children who have developed the ability to counter a forthcoming movement with an opposing postural adjustment.

This chapter investigated the indirect association between task and posture performance present in children over the same developmental time period. Therefore, the findings of this chapter would appear to suggest that, further to the dynamical relationship that gets managed as a function of age, there is a subtle, indirect association between postural and fine motor control.

The findings of this study have practical implications. One implication relates to the assessment of motor ability in children. A number of standardised movement assessment batteries for children (e.g. the MABC-2) test manual dexterity separately to postural control. This arrangement has lacked empirical justification in the past but these results provide a clear rationale for this division; corroborating recent confirmatory factor analysis demonstrating the construct validity of the MABC-2 (Schulz et al., 2011). These findings also raise doubt over the usefulness of combining scores from tests of manual dexterity and postural control. A number of assessment batteries provide a composite score that indicates a child’s overall motor proficiency. The implicit assumption in such practice is that there is an underlying construct of ‘general motor ability’. The results of this study suggest that this construct may not have validity. Indeed, children who experience difficulties in motor development often have a deficit in fine but not gross-motor skills and vice versa (Zwicker et al., 2012; Visser, 2003). On this basis, it can be argued that the production of a combined motor performance score is not useful and might actually mask a profound deficit in one domain. This suggests that is it more useful to provide these scores separately and flag when a child is falling under an acceptable level (e.g. the fifth percentile (Blank et al., 2012)) and intervene accordingly.

The argument for presenting postural measures separately from manual skill scores when assessing children does not imply that those children with the most profound movement problems will not have difficulties in both domains. It may be that children with pathological difficulties such as cerebral palsy and DCD struggle with both gross and fine-motor tasks. It is easy to imagine that deficits in these different systems interact (the ‘double whammy’) to create considerable difficulties when engaging in activities of daily living (ADLs). It is also possible that a deficit in either domain might act as a barrier to a particular ‘higher-order’ activity (e.g. pulling on a sock when standing might be made difficult by poor balance or poor dexterity). The extent to which these theoretical possibilities reflect clinical reality requires further empirical investigation.

Indeed, in the absence of evidence for a strong link between posture and manual-control development beyond infancy, it would appear inadvisable to use empirically un-validated theoretical models such as the ‘proximal-distal’ theory (Rosenblum and Josman, 2003) as a guiding when planning therapeutic interventions. Instead, as a recent meta-analysis of intervention studies used to treat children with DCD suggests (Smits-Engelsman et al., 2013), approaches that take a ‘task’ as opposed to ‘process’ orientated approach to intervening appear much more effective (i.e. identifying activities a child struggles with and focussing therapy on supporting them to improve performance in these ADLs, as opposed to focussing on assumed core-deficits in physiological or psychological functioning that underlie the condition).

A better understanding of the relationship between deficits in posture, manual dexterity and ADLs would allow more tailored interventions for children with movement problems. The findings of this study suggest that poor performance in one domain is not necessarily a reliable indicator of difficulties in another domain. This suggests that a child with manual dexterity problems may not benefit from a therapeutic approach that encourages improved posture. It follows that each child should be assessed in depth to produce a profile of their strengths and weaknesses. This would allow targeted therapy so the child with postural difficulties could receive help with maintaining balance whereas the child with manual control problems could obtain help directed towards improving their manual dexterity. The objective measures described in this study could allow therapists to provide such targeted interventions.

Summary of experimental chapters

Chapter 1: Sex differences in fine-motor control

To what degree does being male or female influence the development of manual skills in pre-pubescent children? 422 children were tested on their ability to control a handheld stylus, using objective kinematic measures to explore their performance on tasks that tapped into specific aspects of manual control. The task battery exploited tablet PC technology to present interactive visual targets on a computer screen whilst simultaneously recording the participant's kinematic responses (via their interactions with the stimuli through the handheld stylus). The battery required children to use the stylus to: (i) make a series of aiming movements, (ii) trace a series of abstract shapes and (iii) track a moving object. The tasks were not familiar to any of the children, allowing measurement of a construct that might be meaningfully labelled 'manual control' whilst minimising culturally determined differences in experience (as much as possible). A reliable interaction between sex and age was found on the aiming task, such that girls' movement times were faster than boys' in younger age groups (e.g. 4-5 years) but with this pattern reversing in older children (10-11 years). The improved performance in older boys on the aiming task is consistent with young adult males having faster reaction times and shorter movement durations than their female peers and can be explained by neuromuscular differences. A small but reliable sex difference was found in tracing skill, with girls showing a slightly higher level of performance than boys irrespective of age. There were no reliable sex differences between boys and girls on the tracking task. Overall, the findings suggest that prepubescent girls have superior manual control, but small population differences do not suggest that boys and girls require different educational support whilst developing their handwriting skills.

Chapter 2: Measuring children's head movements and postural stability in visual and manual tracking tasks

Manual dexterity requires that the head and body are held steady so vision can guide error corrections. Both manual dexterity and postural control improve throughout a child's development, which leads to changes in the synergistic relationships between head, hand and posture. Nevertheless, the relationship has not been well investigated, probably because of the technical difficulties in recording movements concurrently. A system was developed to be capable of recording head, hand and posture data simultaneously and was tested its use in four groups aged 5-6 years (n = 8), 8-9 years (n = 10), 10-11 years (n = 7) and 19-21 years (n = 9). HR and CoP were measured under three conditions: (i) baseline (stable fixation); (ii) fixating a target moving at three speeds; (iii) manually tracking the moving targets. The visual tracking task did not alter postural movement (HR and CoP) relative to baseline in adults, but in children movement (HR and CoP) increased relative to baseline, with a larger effect for faster moving targets. The manual tracking task increased HR in all groups (the younger the group, the worse the tracking performance and the greater the HR) and this effect increased for faster moving targets. The manual tracking task was associated with greater CoP movement in children but less so in adults, suggesting predictive postural compensation mechanisms for arm movements develop during childhood.

Chapter 3: A new tool for assessing head movements and postural sway in children

Current methods of measuring gross-motor abilities in children involve either high cost specialist apparatus unsuitable for use in schools or low non-optimal observational measures.

The development of a low cost system that is capable of providing high quality objective data for the measurement of head movements and postural sway is described. This system has huge potential for assessing children in school settings, and thus provides a mechanism for identifying children with neurological problems affecting posture. In order to test the utility of the system we installed it in two schools to determine whether we could collect meaningful data on hundreds of children in a short time period. The system was successfully deployed in each school over a week and data collected on all the children within the school buildings at the time of testing (n = 269). The data showed the patterns predicted from previous small scale studies that used specialist apparatus to measure childhood posture. The system presented in this study has great potential to allow screening of children for gross postural deficits in a manner that has never been possible previously. It follows that this system opens up the exciting possibility of conducting large scale neuroscience studies concerning the development of posture.

Chapter 4: Children's seated postural stability as a function of task demands

A stable platform is required for precise manual control, but arm movements can destabilise posture by shifting the body's CoM. The interaction between posture and arm movements appears to produce a 'catch 22' situation for the developing nervous system. This impasse can be avoided by reducing the postural demands through the simple action of sitting down whilst performing complex manual tasks. Indeed, fundamental educational skills (e.g. handwriting) are usually acquired when sitting at a desk. In this study, we examined the extent to which the postural stability of primary school children is influenced by the provision of a standard school chair whilst they performed manual control tasks. It was hypothesised that different manual tasks would differentially impact postural stability. Tracing a complex shape appears to require (and allow) a stable platform. Aiming tasks are more ballistic in nature and we hypothesised that such movements would perturb posture. Manual tracking of a predictably moving target allows for minimal postural disruption if children can compensate for the expected changes in CoM produced by the arm movements. Postural stability and head movements of children aged between 5-9 years (n = 63) was measured, finding that: (a) seating attenuates the differences in postural control normally observed as a function of age; (b) postural control is modulated by task demands (increased stability when tracing, decreased stability when generating aiming movements and minimal disruption to stability when tracking a predictably moving target).

Chapter 5: The relationship between postural stability and manual control in children

The neural systems responsible for postural control are separate from the neural substrates that underpin control of the hand. Nonetheless, postural control and eye-hand coordination are linked functionally (as a stable platform is required for precise manual control). For example, postural control in early childhood is a prerequisite for the development of many fine-motor skills (skills that simply cannot develop until the child is able to sit or stand upright). This raises the issue of the empirical relationship between measures of gross-motor skill (postural stability) and fine-motor (manual) control. Objective measures of postural stability were recorded and manual control in a sample of school children (n = 277) aged 3-11 years in order to explore the extent to which measures of manual skill could be predicted by measures of postural stability. A significant but modest correlation was found between separate measures of postural stability and (seated) manual control taken on different days. Regression analysis revealed postural stability accounted for 7% of the variance in manual performance. These data reflect an interdependent functional relationship between manual control and postural stability development. Nevertheless, the relatively small proportion of the explained variance is consistent with the anatomically distinct neural architecture that exists for gross and fine-motor control. These data justify the approach of motor batteries that provide separate assessments of postural stability and manual dexterity and have implications for therapeutic intervention in developmental disorders.

Conclusion

In order to understand how fine-motor skill develops, extremely sensitive equipment and measures are required. Motor skill development is highly variable, nonlinear, complex and discontinuous. In this context, establishing a clear pattern of development across age ranges is difficult making it hard to detect differences attributable to demographics. The precision with which a movement can be measured using ‘pen-on-paper’ tests is limited and this may hinder the detection of between-group developmental differences. Nonetheless, the ability to deploy pen-on-paper battery tests in-situ means that there are advantages to taking the tests to the populations of interest. The advent of motion capture techniques, in various forms, has provided researchers with the ability to probe the construct of these movements in detail, and compare specific subcomponents of the movements. Although portable motion capture and force-platform systems are available, their cost does not make them conducive to large-scale testing outside of the laboratory environment.

This project was undertaken to design a system capable of accurately evaluating the motor skills (postural and fine) of large numbers of children and providing useful measures on the association between postural stability and fine motor ability across different age groups of children. The project used an engineering approach based on using off-the-shelf products. This approach meant it was possible to address the cost limitations which can otherwise negate the feasibility of large scale testing of postural stability, particularly in children. The use of appropriate filtering and data acquisition methodologies allowed a solution that addressed the shortcomings of low cost commercially available hardware. This solution allowed high precision measurements to be made and thus this study has shown that it is possible to produce accurate, meaningful 3D data ideally suited to the measurement of motor skill (posture) in non-laboratory settings. The empirical data collected from the equipment demonstrated that the equipment was capable of detecting subtle effects of gender, age, head movements and vision (eyes open versus eyes closed) across fine and postural motor movements.

The work performed as part of this study demonstrates a significant improvement in the researcher's ability to quantify both gross and fine motor performance than those available using traditional pen-on-paper assessments. Furthermore, the system was developed in such a way as to avoid the technological complexities associated with lab-based equipment and as such was able to be deployed with comparable ease as pen-on-paper assessments. Moreover, the resulting data were able to detect subtle patterns of postural sway development in children using a short 30s sample of postural sway.

The equipment was adapted to investigate the effect of seating on postural control and the research established that the subtle effects of age associated with postural development were dampened although there were task-specific components to postural adjustments when children were seated. Finally, the system detected a small (albeit significant) association between postural movement and fine motor control when these movements were assessed in isolation, suggesting two separate control processes exist but these processes only weakly influence the development of the other over the time course of development.

Thus, the main conclusions that can be drawn from the work in this project are that:

- With sufficiently sensitive measures of fine motor control, subtle effects of gender on motor development were evident across the developmental range.
- The addition of concurrent postural measurement afforded the ability to investigate how postural control and suprapostural tasks interact. The ability of the postural system to act in response to a self-induced perturbation develops over the developmental timescale, with predictive postural control representing maturation of the postural control system in children.

- With an awareness of the limitations of off-the-shelf products, suitable filtering, acquisition and processing methods can be developed which result in a system capable of capturing data equivalent to that obtained by clinical measurement equipment and at a fraction of the cost. Furthermore, this equipment was capable of detecting the effect of closing the eyes in quiet postural stance.
- The equipment can be deployed into the classroom environment and it allows for investigation of postural adaptation in response to reduced postural demands. Observed patterns of postural destabilisation associated with age are attenuated when the demands on the postural system are reduced by seating the individual.
- Postural control is not part of a general motor control construct but interacts on a dependent dynamic level with fine motor control. There is a weak relationship that exists between gross and fine motor control abilities.

Future work

The ability to transport this equipment to particular populations of interest represents an opportunity to study gross and fine motor control in a broad range of developing populations. In particular, the equipment developed as part of this thesis could be used to investigate the role of postural stability in older adults in the context of a risk of falling. By embedding this equipment in a specialist falls clinic or care home, transient postural stability could be monitored routinely (e.g. weekly). In doing so, transient periods of postural instability could be detected and investigated in the context of increased falls risk to the individual. If increased sway was detected, this could conceivably inform an intervention strategy to mitigate the elevated risk of falls associated with postural instability.

This study highlights the difficulty in cross-sectional investigations of postural development. Large cross-sectional studies average out nonlinearities associated with postural development. The ability to monitor transitions between developmental modes of postural control (possibly indexed by significant changes in CoP behaviour, or HM) can only be conducted as part of a longitudinal study (Darrah et al., 2009; Kirshenbaum et al., 2001; Rosenblum and Josman, 2003). A longitudinal study has the principal advantage of taking within subject variability into account, and this may be a better indicator of motor development. Such longitudinal studies would be an obvious progression of research exploiting the equipment and building on the findings made in this study.

In summary, this study has gone some way towards enhancing our understanding of how postural stability develops in conjunction with fine motor performance. The fidelity of the measures used to assess postural movement and fine motor performance, and the empirical findings from them provide a new understanding of how postural control develops over childhood.

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Appendix A: Publication Submitted as Part of Grant-funded Work During PhD

Predicting the Effect of Surface Texture on the Qualitative Form of Prehension

Ian John Flatters[1,2], Loanne Otten[3], Anna Witvliet[3], Brian Henson[2], Raymond John Holt[2], Pete Culmer[2], Geoffrey Parker Bingham[4], Richard McGilchrist Wilkie[1], Mark Mon-Williams[1]*

1 Institute of Psychological Sciences, University of Leeds, Leeds, West Yorkshire, United Kingdom, **2** School of Mechanical Engineering, University of Leeds, Leeds, West Yorkshire, United Kingdom, **3** Pedagogische Wetenschappen en Onderwijskunde, Radboud Universiteit Nijmegen, The Netherlands, **4** Department of Brain and Psychological Sciences, Indiana University, Bloomington, Indiana, United States of America

Abstract

Reach-to-grasp movements change quantitatively in a lawful (i.e. predictable) manner with changes in object properties. We explored whether altering object texture would produce qualitative changes in the form of the precontact movement patterns. Twelve participants reached to lift objects from a tabletop. Nine objects were produced, each with one of three grip surface textures (high-friction, medium-friction and low-friction) and one of three widths (50 mm, 70 mm and 90 mm). Each object was placed at three distances (100 mm, 300 mm and 500 mm), representing a total of 27 trial conditions. We observed two distinct movement patterns across all trials—participants either: (i) brought their arm to a stop, secured the object and lifted it from the tabletop; or (ii) grasped the object 'on-the-fly', so it was secured in the hand while the arm was moving. A majority of grasps were on-the-fly when the texture was high-friction and none when the object was low-friction, with medium-friction producing an intermediate proportion. Previous research has shown that the probability of on-the-fly behaviour is a function of grasp surface accuracy constraints. A finger friction rig was used to calculate the coefficients of friction for the objects and these calculations showed that the area available for a stable grasp (the 'functional grasp surface size') increased with surface friction coefficient. Thus, knowledge of functional grasp surface size is required to predict the probability of observing a given qualitative form of grasping in human prehensile behaviour.

Citation: Flatters IJ, Otten L, Witvliet A, Henson B, Holt RJ, et al. (2012) Predicting the Effect of Surface Texture on the Qualitative Form of Prehension. PLoS ONE 7(3): e32770. doi:10.1371/journal.pone.0032770

Editor: Marc O. Ernst, Bielefeld University, Germany

Received October 31, 2011; **Accepted** January 30, 2012; **Published** March 5, 2012

Funding: IF was funded by an Engineering and Physical Sciences Research Council Collaboration Fund obtained by BH, RW, PC, and MMW. The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Competing Interests: The authors have declared that no competing interests exist.

* E-mail: m.mon-williams@leeds.ac.uk

Introduction

Most humans demonstrate an exquisite ability to manipulate objects with their hands. Expert manual interaction with an object requires the actor to move their hand to the object of interest (the precontact phase) and then apply the appropriate fingertip forces in order to manipulate the object (the contact phase). In the precontact phase, the geometric properties of the object constrain the trajectory of the grasp such that the digits align with the object surface [1,2]. In the contact phase, the physical properties of the object determine the fingertip forces required for manipulation.

In line with this, it has been shown that the textural properties of objects influence the contact phase of prehension [3]. Contact with an object provides haptic information regarding its textural properties and this information is known to be used in programming the appropriate fingertip forces [4]. Nevertheless, vision can provide useful information regarding object properties before the time of contact. Visual information can therefore be used to programme forces in advance, on the basis of memorised textural properties (acquired over the lifespan and/or from immediately preceding object interactions). Forsberg and colleagues have shown that visual information is used in this way, with the properties of an object influencing the fingertip forces programmed in advance of contact [4].

The fact that texture influences the advance programming of fingertip forces implies that an object's texture might affect the precontact phase of the movement. This is particularly important as the influence of texture on the precontact phase of prehension has clinical applications, with a number of older adults experiencing difficulties when handling everyday items (e.g. a hot cup of tea or a saucepan handle). There has been remarkably little investigation of this topic. Weir et al. [5] reported that texture had no impact upon the duration of the precontact phase but low-friction surfaces increased the time that participants spent generating fingertip forces before the object was lifted. In contrast, Fikes et al. [6] did find an effect of texture on the precontact phase, with participants taking longer to move their hand to a low-friction object. Thus there is some empirical evidence that quantitative changes in prehension occur as a function of surface texture. The question of whether surface texture influences the qualitative form of the precontact movement patterns, however, remains unanswered. This question is of particular interest because it has both practical and theoretical implications. If different textures (and their visual appearances) produce different qualitative patterns then, at a practical level, engineers can determine whether different surfaces have the potential to elicit safer behaviour (e.g. can kitchen utensils be made safer for older adults to reach-and-grasp?).

The question is also pertinent to the theoretical issue of action selection: what makes us select one movement pattern rather than another when interacting with objects that afford multiple options? Modern theoretical accounts of motor control suggest that actions are controlled via 'inverse models' – neural circuits that have become reinforced because their activation produces the desired movement pattern when triggered by a given input stimulus [7]. It is thought that multiple inverse models are housed within the brain, with many of these models sharing common neural architecture. In this conceptual framework, the acquisition of a new skill occurs through the modification of an existing neural circuit, producing a new internal model that is precisely tuned to specific environmental conditions. This postulated mechanism allows the acquisition of complex skills through the merger of a series of discrete movements that achieve particular goals. The resulting 'higher-order' behaviour might result in 'lower-order' movements unfolding concurrently or in rapid sequential order. This can be conceived as a process where 'higher-order' models recruit 'lower-level' models (in the same way that sub-routines are called within a complex computer programme). The notion of multiple inverse models suggests that a small environmental change (e.g. a different surface texture) might be sufficient to trigger a different higher-order inverse model and thus elicit a qualitatively different action - despite the task appearing to require the same class of movement. There have been few empirical investigations into this topic, hence our interest in the issue of whether surface texture can influence the qualitative prehension movement pattern.

Mon-Williams and Bingham [8] have shown that two distinct movement patterns can emerge when participants are asked to reach-and-grasp an object and lift it off a tabletop (see Figure 1). In some cases, participants stop their arm moving forward before the fingers make contact with the object, adjust finger position and then grasp and lift (so-called 'stop' movements). In other cases, participants contact the object whilst the hand is still moving (so-called 'on-the-fly' movements). If the safety margins of the task decrease (e.g. by making the object wider and closer to the maximum grasp aperture) then the proportion of on-the-fly movements also decreases. This observation suggests that the probability of observing a particular movement pattern is affected by the margins of safety. On these grounds, we hypothesised that changes in an object's surface texture might alter the proportion of on-the-fly movements, because altering texture affects the safety margins (see Figure 2, Lower Panel).

In order to explore the manner in which humans interact with objects of different textural properties, we asked participants to reach-to-grasp and lift objects from a tabletop while experimentally manipulating object width, distance and surface texture. We expected that changes in the distance of the object would produce the normal lawful changes in the reach kinematics (higher peak speeds and longer durations for further distances). More importantly, Mon-Williams and Bingham's [8] findings led us to predict that decreasing the surface friction would decrease the proportion of on-the-fly movements.

Methods

Twelve unpaid participants from the University of Leeds were recruited (7 female; age mean 27.7 years, age range 20.5–47.1 years; 11 reported right hand preference). All participants had normal or corrected-to-normal vision and no history of neurological deficit. Maximum pinch grip aperture was measured for each participant using a ruler (mean 15.8 cm, range 13.0–21.0 cm). All participants provided informed consent prior to inclusion in the study. The study was approved by a University ethics committee and was performed in accordance with the ethical standards laid down in the Declaration of Helsinki.

The stimuli were manufactured by mounting a plastic (nylon, black) cylinder (25.4 mm diameter) on a wooden block (Figure 2, Upper Panel). The ends of each plastic cylinder were machined to a 25 mm radius. Participants grasped along the long axis of the cylinder between the thumb and index finger. Three object widths were used (dimension A: 50, 70 and 90 mm, Figure 2, Upper Panel) while the distance between spherical centre-points of the grip surfaces (dimension B: 0, 20 and 40 mm, Figure 2, Upper Panel) and the wooden mounting block width (dimension C: 33, 53 and 73 mm, Figure 2, Upper Panel) varied proportionally to the object width. For each of the three object widths, there were three different surface textures applied to the grasp surfaces, such that three distinct coefficients of friction would be generated: High (μ_H), Medium (μ_M) and Low (μ_L). The high-friction surface was generated by sticking coarse-grade sandpaper (Aluminium Oxide, P50) to the grasp surfaces. The medium-friction surface was the untreated machined plastic. The low-friction condition was achieved through the application of petroleum jelly (Vaseline®, Unilever) with a soft-bristled brush to the participant's fingertips and the grasp surfaces of the machined plastic stimulus (application was repeated on alternate trials).

To confirm that manipulation of the coefficient of friction was occurring at the fingertip interface, the coefficients of friction (μ_H, μ_M and μ_L) were calculated experimentally using apparatus developed by Shao, et al. [9]. Each sample was placed on a two-axis load cell and a vertical load of approximately 1N was applied (Y-axis) through the silicone fingertip onto the sample. A horizontal displacement of the fingertip was applied at 10 mm/s (X-axis) until the fingertip was clear of the sample. Force data were sampled at 1000 Hz in the X and Y components. Each test was repeated three times. The data were filtered using a dual-pass Butterworth second order filter with a cut-off frequency of 16 Hz (equivalent to a fourth order zero phase lag filter of 10 Hz). The coefficient of static friction was calculated by dividing the maximum value of horizontal force by the component of vertical force at the corresponding time point.

To ensure a consistent starting position, the participants pinched a raised origin marker positioned 100 mm from the front edge of the study table prior to the start of each trial. The objects were placed at distances of 100, 300 and 500 mm beyond the origin point, in line with the midline of the participant. Participants were instructed to reach and grasp the object as quickly and as accurately as possible between the pads of the forefinger and thumb, lift the stimulus from the table and hold it in a static raised position until told to lower the object to the table and return to the start position in preparation for the next trial. Participants were instructed to begin movement when they heard a verbal "go" command at the end of a verbal countdown, i.e. "three, two, one, go". Data acquisition was initiated when the participant was still pinching the origin point (at the count of "one"), and the hold phase of the movement lasted between 0.5 s and 1 s.

The factors of object width and distance were presented in a pseudo-randomised order. Participants were blocked and counterbalanced on the factor of surface friction coefficient. The three object widths, three object distances and three coefficients of friction represented 27 conditions, each of which was repeated 10 times, resulting in a total of 270 trials. The test session typically lasted 1 hour. Trial repetition criteria included: (i) Failure to grip the stimuli on the instructed surface; (ii) Inability to achieve stable, static grip of the stimuli; (iii) Knocking the stimuli over; (iv)

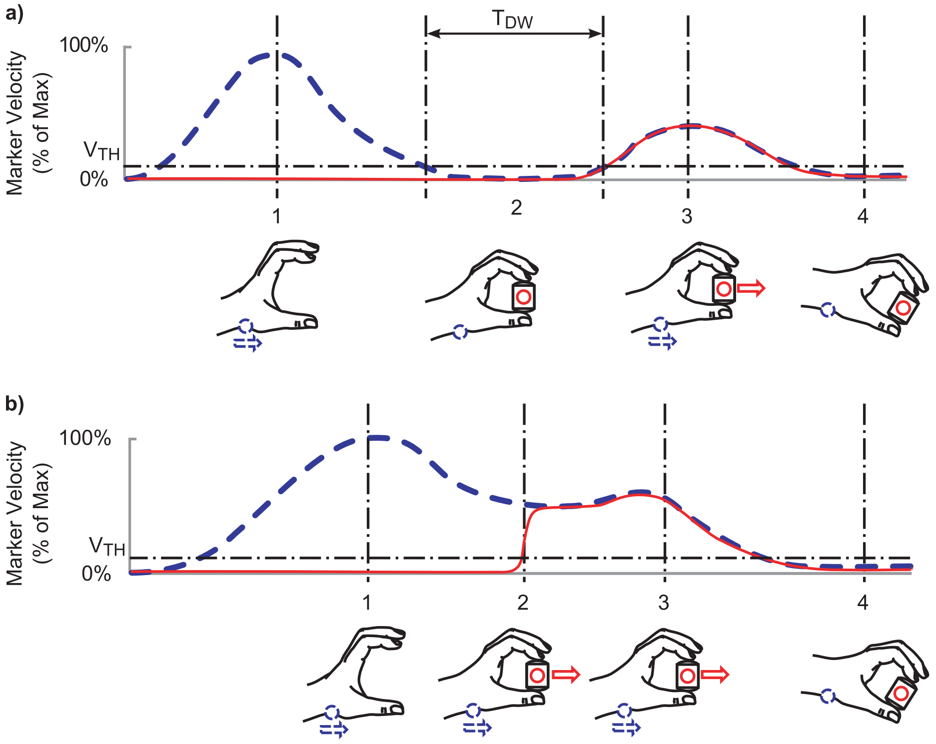

Figure 1. Kinematic profiles for stop and 'on-the-fly' prehension movements. *Upper* A velocity profile typical of a stop movement: 1, the hand is in the transport phase with the wrist IRED reaching peak velocity. 2, as the hand and fingers approach the object the hand velocity drops below the threshold velocity (V_{TH}) and remains below threshold velocity or stops for a period (T_{DW}). 3, upon successful application of the grip, both the wrist and object markers move in unison as part of a second distinct movement. 4, movement complete – hand and object velocity tends to zero. *Lower* A velocity profile typical of a 'fly-through' movement: 1, the hand is in transport phase toward the object. 2, as the fingers contact the object, the wrist IRED velocity is maintained above the threshold velocity (V_{TH}) as the object is gripped. 3, the hand and object continue to move in unison while the wrist IRED velocity remains above the threshold velocity. 4, movement complete, hand and object velocity tends to zero.
doi:10.1371/journal.pone.0032770.g001

Dropping the object prior to, or shortly after, the verbal return command. Following failure of a trial, the condition under which failure occurred was recorded and the participant returned to the origin and repeated the trial. In the low-friction object condition, 4.1% of trials required repetition compared to a repetition rate of 2.4% across all trials. This procedure ensured that 10 trials for each condition were completed.

Kinematic data acquisition was performed using an Optotrak 3020 motion tracking system (Northern Digital, Ontario, Canada). The positions of four Infra Red Emitting Diodes (IREDs) were acquired at 100 Hz for three seconds for the high-friction and medium-friction conditions and for four seconds on the low-friction conditions (because the low-friction surface took longer to pick up). The first two markers were attached to the reaching hand at the index finger (distal medial corner of the finger) and the thumb (distal lateral corner of the thumb). These markers were used to measure grip aperture. The third marker was placed on the styloid process of the wrist to provide an independent measure of hand movement. A fourth marker was placed on the wooden block of the stimuli facing away from the participant to identify when the object was lifted off the tabletop. All data were filtered using a dual-pass Butterworth second order filter with a cut-off frequency of 16 Hz (equivalent to a fourth order zero phase lag filter of 10 Hz). The distance between the thumb and index finger IREDs (the aperture) was then computed. Following this operation, the speed of the wrist IRED and the aperture was computed and the onset and offset of movement together with the peak speed was estimated using standard velocity threshold and peak picking algorithms (threshold for movement onset and offset was 50 mm/s as per Munro et al. [10]). The criterion for onset of a reach was wrist velocity exceeding 50 mm/s. The criterion for cessation of reach movement was wrist velocity falling below 50 mm/s. The deceleration phase was defined as the time between peak speed and the offset of reach movement. The object's 'time-to-lift' was designated at the point when the fourth IRED's velocity exceeded 50 mm/s. The critical issue was whether movements were 'stop' or 'on-the-fly'. Movements were classified as 'stop' if there was a temporal gap between the cessation of wrist movement and the onset of movement of the object. Movements were classified as 'on-the-fly' if the wrist velocity was maintained above the threshold velocity from the onset of wrist movement to the onset of object movement. This procedure allowed a simple objective classification of the different movement types (see Figure 1). Visual inspection of the trials confirmed that this objective classification was rational – there was a clear bifurcation whereby the hand would either clearly stop before the lift or the object was grasped whilst the hand was still travelling above the threshold velocity.

The mean value across the 10 trials for each dependent variable of interest for each individual participant was entered into a 3 (Distance)×3 (Width)×3 (Surface Texture) repeated measures ANOVA (a separate ANOVA for each dependent variable of interest).

Results

"On-the-fly" Movements

The proportion of on-the-fly movements was affected by the grip surface ($F(2,22) = 20.15$, $p<0.01$) and object width

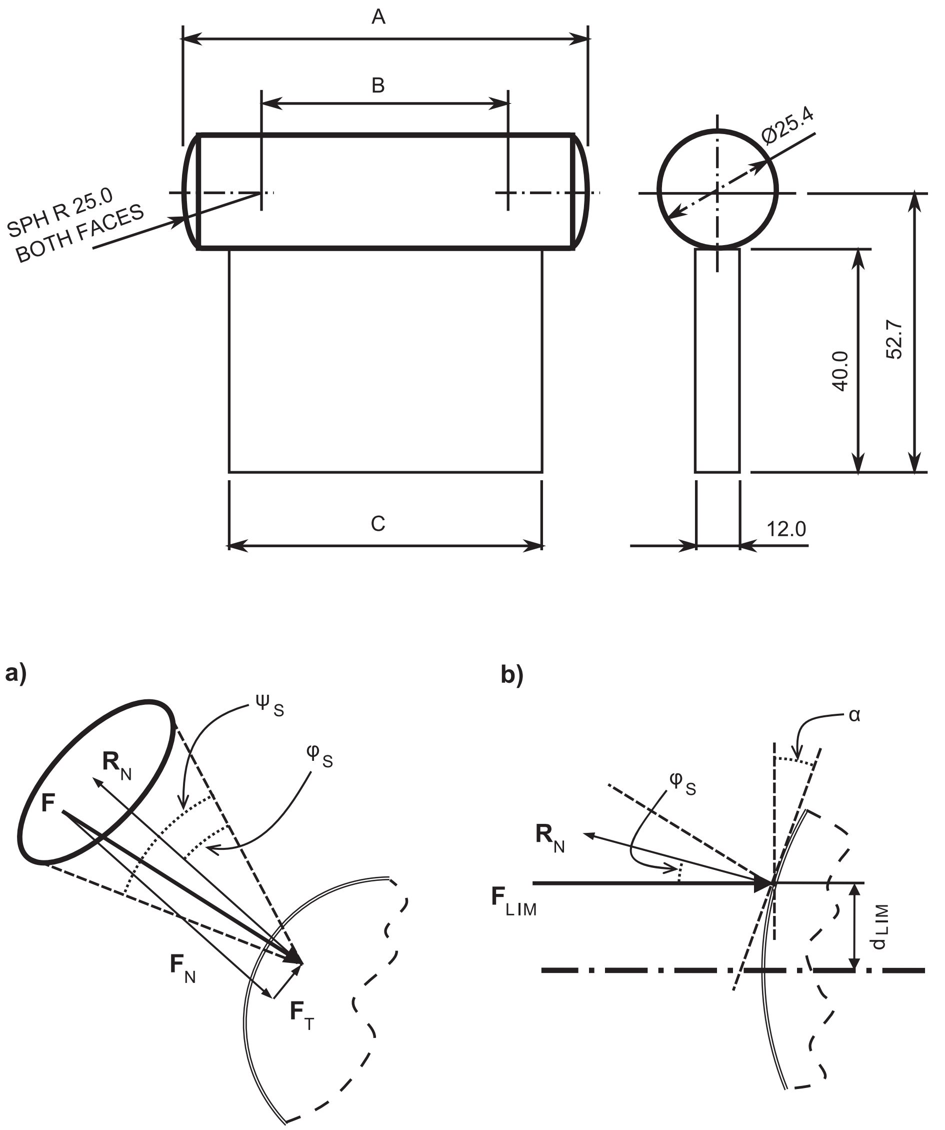

Figure 2. Object geometric properties friction-dependant functional grip area. *Upper* Geometric variation in stimulus sizes: Grip surface width 'A', the distance between the spherical surface centre-points 'B' and support base width 'C' were varied as discussed in the Method section. *Lower a)* Manually securing an object requires the frictional force to be greater than the tangential component of object weight at the interface between fingertip and object. A curved surface results in a normal reaction force direction (R_N) unique to the point at which the object is grasped. Fearing [14] demonstrated that, for a stable grasp, the grip conditions should satisfy: $\tan^{-1}|F_t|/F_n < \tan^{-1}\mu$ or $\mu F_n > |F_t|$. For a stable lift, fingertip force should be applied within an angle of ϕ_s relative to the normal reaction force (R_N), where: $\phi_s = \tan^{-1}\mu_s$. Extending this relationship in the direction of all tangential friction force directions generates a cone of friction of half-angle ϕ_s and cone angle ψ where: $\psi = 2\ \phi_s$. *b)* As force is applied to the curved surface at a distance d_{LIM} from the centreline of the radius, then the force is at an angle α to the surface normal. When $\alpha = \phi_s$ the force lies at the limit of the cone of friction. An increase in d results in the force lying outside the cone of friction and unstable grasp. Thus ϕ_s, and d_{LIM} are linked to the coefficient of static friction μ_s such that an increase in μ_s extends the functional area which can be grasped to achieve a stable grasp.
doi:10.1371/journal.pone.0032770.g002

($F(2,22) = 8.60$, $p < 0.01$) (Figure 3), with a statistically reliable interaction between the two ($F(2,22) = 4.34$, $p < 0.05$, $\varepsilon = 0.77$). The narrow width object produced a similar proportion of on-the-fly movements in the medium and high friction conditions. It is not clear why this was the case, but the clear difference between these conditions and the low-friction target is the critical finding. We found no effect of distance ($F(2,22) = 0.91$, $p = 0.41$), nor interactions of distance with width or surface texture. We explored the data to determine whether stop movements reliably followed a failed trial or whether 'hysteresis' could be observed in the data (where one trial influences the next) but we were unable to identify any discernible pattern.

The peak speed of the movement was affected by object distance ($F(2,22) = 241.88$, $p < 0.001$, $\varepsilon = 0.518$) but not by width or texture or interactions. Increased reach distance caused a longer Movement Time (MT) ($F(2,22) = 36.27$, $p < 0.01$, $\varepsilon = 0.77$). There was a two way interaction between texture and object width, with MT increasing as the surface friction decreased and these effects being more pronounced when the object was wider ($F(4,44) = 35.33$, $p < 0.01$, $\varepsilon = 0.76$). The MT increases could be explained through a prolonged deceleration phase, so there was a two way interaction between texture and object width, with deceleration time increasing as the surface friction decreased and these effects being more pronounced when the object was wider ($F(4,44) = 7.46$, $p < 0.01$, $\varepsilon = 0.41$).

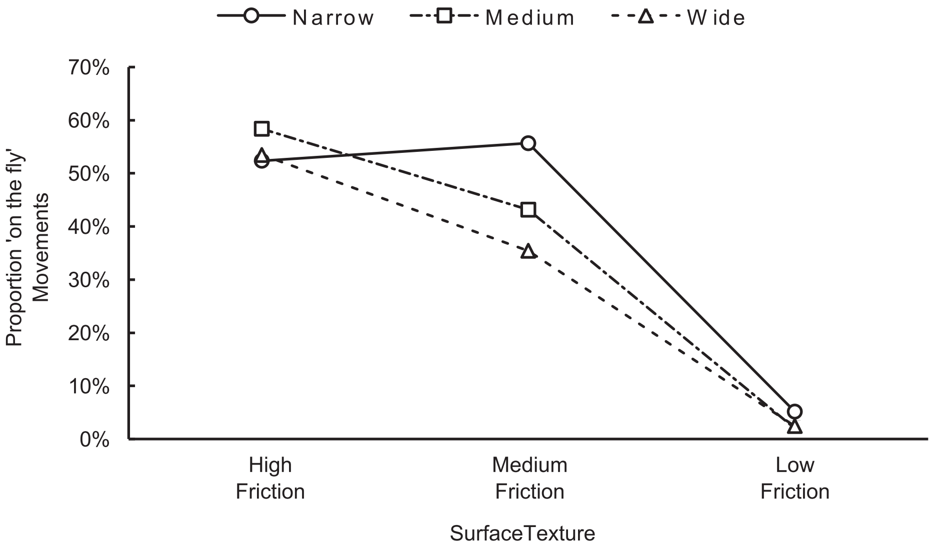

Figure 3. Proportion of 'on-the-fly' movements as a function of surface texture. The mean coefficient of static friction was 1.31, 0.76 and 0.44 for the high, medium and low friction object surface textures respectively (see Methods).
doi:10.1371/journal.pone.0032770.g003

Discussion

Humans are complex systems and human behaviour is notoriously difficult to predict. But behaviour is not random and invariant patterns can be found in tasks such as reaching-to-grasp objects [11]. For example, the duration of the movement is lawfully related to the distance of the object to be grasped [12]. Thus, it is possible to predict the quantitative relationship between duration and object distance for a given individual carrying out a particular prehensile task [13]. The present study explored whether we might find similar invariant patterns in the *qualitative* form of reach-to-grasp movements. Mon-Williams and Bingham [8] have shown previously that the instruction to reach, grasp and lift an object from a tabletop produces two distinct movement patterns. In some cases, the participants move their hand to the object, stop, secure a grasp, then lift the object upwards. In other cases, participants grasp the object 'on-the-fly' such that the arm does not stop moving while the object is secured between the digits. We hypothesised that the proportion of these different movement patterns would be affected by the surface texture of the objects being grasped. In order to test this hypothesis we used three textures and studied whether the surface influenced the proportion of on-the-fly movements. The data showed unambiguously that surface texture altered the way in which participants interacted with the objects. The low-friction surface almost invariably caused participants to stop their arm moving forward before securing the object between the index finger and thumb, and then lifting the object from the tabletop. Thus, the behaviour was sequential in nature, with the reach, grasp and lift component occupying its own temporal space. In contrast, the reach, grasp and lift components were frequently merged into a single 'higher-order' behaviour with a high-friction surface texture.

The findings indicate that predicting the mode of human prehension requires knowledge of the object surface texture. In the case of the low-friction object, one can predict with reasonable certainty that individuals within the age range of 20–50 years will not show on-the-fly behaviour under these task conditions. The situation is more interesting with the high-friction surface texture. On average, on-the-fly behaviour is most likely to be seen over a series of repeated lifts, but it is not possible to be certain on any given trial whether the participant will stop before grasping. In the case of the medium-friction surface, it is close to chance as to whether the participant will stop or fly through.

It is of note that the peak speed of the movement was unaffected by the texture of the objects. The modular organisation of movements via multiple inverse models (as outlined in the introduction) is consistent with this finding. Multiple inverse models allow the system to acquire complex skills by combining 'lower-order' actions in countless ways and provide flexibility for tailoring behaviour to precise environmental conditions. In the present example, the goal directed behaviour can be conceived as three separate actions ('reach', 'grasp' and 'lift') underpinned by internal models that can be organised to unfold sequentially (the higher-order 'stop' behaviour) or concurrently ('on-the-fly'). Such organisation is efficient as it allows recruitment of similar neural circuits (and thereby produces movements that show great similarity in the initial stages). It seems reasonable to assume that 'stop' reaches to the low-friction object were selected from the outset (given that this behaviour was almost inevitably observed on every trial). In the high-friction case, it is not possible for us to determine what action was initially selected. Mon-Williams and Bingham [8] have shown previously that participants can switch from 'on-the-fly' to 'stop' patterns as the movement unfolds in response to online feedback. This suggests that it might be possible after the event to identify factors that influence the qualitative movement pattern observed, but prediction before the trial starts must be probabilistic in nature.

The results from the rough object (where some movements were on-the-fly and some were stop) reveal the inherently probabilistic nature of predicting human behaviour. Nevertheless, an understanding of the probabilities of observing different behaviours allows the scientist to better predict the outcome of a given reach-to-grasp task. Weir et al. [5] and Fikes et al. [6] have previously reported a quantitative effect of texture on the precontact phase of prehension, with participants taking longer to move their hand to a low-friction object. The data from the current study support these previous observations. It follows that a complete description of reach-to-grasp behaviours requires knowledge of surface texture if the qualitative and quantitative form of the movement is to be predicted, though predictions about this human behaviour remain probabilistic in nature (especially, as observed by Neils Bohr, if the predictions are made in advance).

Author Contributions

Conceived and designed the experiments: MMW RW GB PC RH BH IF. Performed the experiments: IF AW LO MMW RW. Analyzed the data: IF AW LO MMW RW. Contributed reagents/materials/analysis tools: MMW GB RW BH. Wrote the paper: IF MMW RW LO AW RH BH PC.

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