Even Granerud

Changes in Posture and Balance Performance during Five Days of Wobble Board Training

Master thesis in Sport Sciences
Department of Physical Performance
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Oslo, 2013.

Even Granerud

Abstract

Introduction: Human postural control is facilitated through postural movements such as ankle-, hip-, or multi-joint strategies. Principal component analysis (PCA) applied to kinematic marker offers a novel approach study the structure of postural movements by identifying and quantifying correlated segment motion. This study investigated if the structure of the postural movements changes as subjects learn to master a balance task (standing on a wobble board). It was hypothesized that the relative contribution of principal components quantifying the main types of body sway (e.g. ankle strategy) to the whole postural movements would decrease as subjects improved in performance, while the contribution of higher-order movement components would increase. **Methods:** Eleven healthy male volunteers (age 25.1±1.7, weight 77.2±5.8 kg, height 1.80m±0.07) conducted a total of 25 120-second quiet stance trials on a wobble board, 5 trials per day during 5 consecutive days. The subjects' postural movements were recorded with a standard 3D-camera system (ProReflex, Qualisys INC., Gothenburg, Sweden) using 49 reflective markers distributed over all major body segments. For each timeframe, a 147-dimensional posture vector was defined that included all marker coordinates. The posture vectors of all trials of a subject were normalized and assembled into an input matrix for the PCA. The structure of a subject's postural movements was then characterized by calculating the relative contribution (RC) of the first 10 principal movement components (PCs) to the entire postural variation in one trial. For each trial, a "balance score" was calculated by totalling the standard deviation of the vertical position of 4 markers placed on the wobble board. A repeated measures ANOVA (Sidak correction) was conducted to determine differences in RC or balance score between trials. **Results:** Balance performance on the wobble board improved over the first 2-3 test days with the balance score decreasing from 52.1±11.0 in the first trial to levels below 34.2±6.1 in all trials of the 4th and 5th day (mean±stdev). This change was significant ($F(1,24)=11.17$, $p<0.007$). However, no systematic changes were observed in the structure of the postural movements as quantified by the first 10 PCs: $F(1,24)<1.42$, $p>0.98$ in the RC calculated for the first 10 PCs. **Conclusion:** The hypothesis was not confirmed. The results of this study suggest that the improvement in performing the wobble-board balance task was not related to changes in the structure or organization of postural movements as quantified by PCA-RC.

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1. Introduction

In everyday life posture and balance is applying to all of us through obtain equilibrium in gait, running, standing, climbing stairs and so on. To obtain decent balance skills is particularly important in the elderly, as falling is a major cause of injury, thus balance exercises are recommended as an intervention program (Ungar et al., 2013). Balance skills could also be a risk factor of sustaining injuries in sports and association between knee injuries and balance has been shown (Paterno et al., 2010).

Wobble board and/or balance board is a frequently used device in rehabilitation, injury prevention and improvement of postural control (Fitzgerald, Trakarnratanakul, Smyth, & Caulfield, 2010; Karime, Al-Osman, Alja'am, Gueaieb, & El-Saddik, 2012; Ogaya, Ikezoe, Soda, & Ichihashi, 2011). Balance and postural control have been shown to improve when training specific exercise tasks on a balance board, and studies has shown that performance parameters indicate stabilometric measurements to improve both in elderly, healthy, young and injured subjects (Ogaya et al., 2011; Fitzgerald et al., 2010; Ko, Challis, & Newell, 2003; Dougherty, Kancel, Ramar, Meacham, & Derrington, 2011). Studies with centre of pressure data and moving platforms show that balance is a modifiable skill as it has shown to improve by training after few sessions (Granacher, Gollhofer, & Kriemler, 2010; Holm et al., 2004).

Human postural control is facilitated through postural movements such as ankle-, hip-, or multi-joint strategies (Winter, 1995). Standing on a wobble board is a complex task which demands a high level of postural control. A search on google.scholar.com and ncbi.nlm.nih.gov/pubmed show that there are 5,790 and 138 articles referred to “wobble board” or “balance board”, respectively. The majority of these articles address rehabilitation, injury prevention and neuromuscular diseases. It is therefore interesting to investigate the changes in movement strategies and postural control in healthy subjects.

Principal component analysis (PCA) applied to kinematic marker offers a novel approach to study the structure of postural movements by identifying and quantifying correlated segment motion (Federolf, Roos, & Nigg, 2012). PCA can be a valuable tool to detect new sources of variability compared to traditional biomechanical features such as centre of pressure obtained from force platforms and joint angle analysis (Mantovani, Lamontagne, Varin, Cerulli, & Beaule, 2011). PCA applied to human kinematics give the opportunity to extract the variance between different movement strategies, showing for example the distribution of ankle- or hip-strategies and their total contribution of variance in a specific task.

In this study the postural movements when standing on a wobble board were investigated. The following chapter will first give an overview of important aspects that are known about postural control. Then, one method that can be used to quantitatively assess postural movements, principal component analysis, will be discussed. When improving the postural control during standing on a wobble board, it was expected that changes in the structure of the kinematic movement patterns would occur and the principal component analysis method offers a new tool to study such changes.

2. Objective

Previous research showed that ankle and hip strategy have a relative long latency after a perturbation (Ting, 2007). Furthermore, both of these strategies involve large parts of the body, i.e. they have to move a big mass. However, other degrees of freedom are available to a subject standing on the wobble board, e.g. shoulder or arm movements, etc. These movements might be able to react faster, e.g. due to the smaller effective mass that they have to move. When somebody improves in balancing on the wobble board, then, one way of accomplishing that could be to rely less on the ankle and hip strategy and more on higher movement components like shoulder or arm movements. Principal component analysis is a method well suited to investigate this assumption. Therefore the purpose of this study was to investigate if the structure of the postural movements changes as a group of subjects learn to master a balance task (standing on a wobble board). Two hypotheses were made:

H_1: There is a statistical association between the improvement of balance performance on a wobble board and the number of attempts.

H_1: The relative contributions of principal components quantifying the main types of body sway (e.g. ankle strategy) to the whole postural movements decrease as subjects improve in balance performance, while the contribution of higher-order movement components increase.

3. Theoretical background

Balance and stability is a task that all healthy human beings are able to master to a certain extent. The ability to control our body's position in space is fundamental to everything we do, hence all tasks require postural control. Every task has an orientation component and a stability component, however the stability and orientation requirements vary with the task and the environment (Shumway-Cook & Woollacott, 2007). For example, the stability and orientation demands change dramatically when standing on a flat stable surface versus balancing on a wobble board, or walking on a treadmill versus walking on a forest trail. In addition, stability limits are affected by many other factors, such as fear of falling and perception of safety (Pai, Maki, Iqbal, McIlroy, & Perry, 2000). The mechanisms making us able to maintain equilibrium and stability are far from fully understood. Major challenges are created to our balance control system because of the fact that we as humans are bipeds which results in a small base of support (BOS) (Winter, Patla, Ishac, & Gage, 2003; Alexandrov, Frolov, Horak, Carlson-Kuhta, & Park, 2005). Humans are an inherently unstable system unless a control system is continuously acting because two-thirds of our body mass is located two-thirds of body height above the ground (Winter, 1995). Despite this, humans are able to adapt and learn to master advanced motions with and without external perturbations. For example, we can observe circus acrobats who show amazing balancing stunts, such as standing on several layers of cylinders with different orientations in the horizontal plane, so that minor deviations of the centre of mass in either direction could cause the whole "tower" to collapse (Wulf, Weigelt, Poulter, & McNevin, 2003). Loss of balance is a clinically important problem, as falls are a primary cause of injury and accidental death in older adults (Minino, Arias, Kochanek, Murphy, & Smith, 2002).

3.1 Basic terms

Posture describes the orientation of any body segment relative to the gravitational vector (Winter, 1995). In general the ability of an individual to assume and maintain a stable position is referred to as balance or stability, where the concept of stability is closely related to equilibrium where equilibrium refers to the resistance to both linear and angular acceleration (Hamill & Knutzen, 2009). However there is no universal definition of posture and balance, or agreement on the neural mechanisms underlying the control of these functions (Shumway-

Cook & Woollacott, 2007). The variability of postural actions emerges from an interaction of the individual, the task with its inherent postural demands, and the environmental constraints on postural actions. The centre of mass (COM) is a point equivalent to the total body mass in the global coordinate system (GCS), that is a balance point of a body; the point about which all of the mass particles of the body are evenly distributed (Hall, 2007). The COM is closely related to centre of gravity (COG), which is the point where all of the body's mass seems to be concentrated; the vertical projection of the COM onto the ground (Hamill & Knutzen, 2009; Winter, 1995). A representation of the weighted average of all the pressures over the surface of the area in contact with the ground is called the centre of pressure (COP), which is the point location of the vertical ground reaction force vector (Winter, 1995). The COP moves continuously around the COM to keep the COM within the support base (Winter, 1995). COP is however totally independent of the COM. Base of Support (BOS) is defined as the area of the body that is in contact with the support surface (Shumway-Cook & Woollacott, 2007). Figure 3.1 show an illustration of COM, COP, COG and BOS.

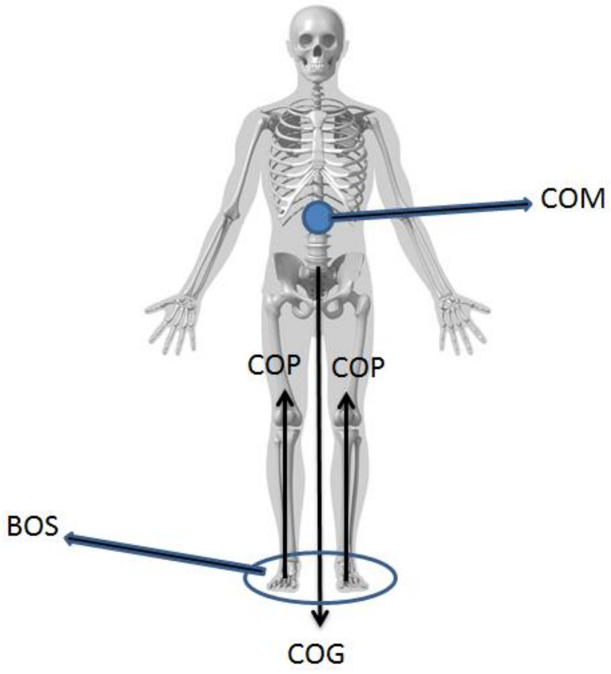

Figure 3.1 *Graphical illustration of COM, COP, COG and BOS.*

The ability to maintain postural control for stability and orientation as humans consists of a number of physiological factors linked together in a complex system. Figure 3.2 show a schematic distribution of the factors, which will be briefly described.

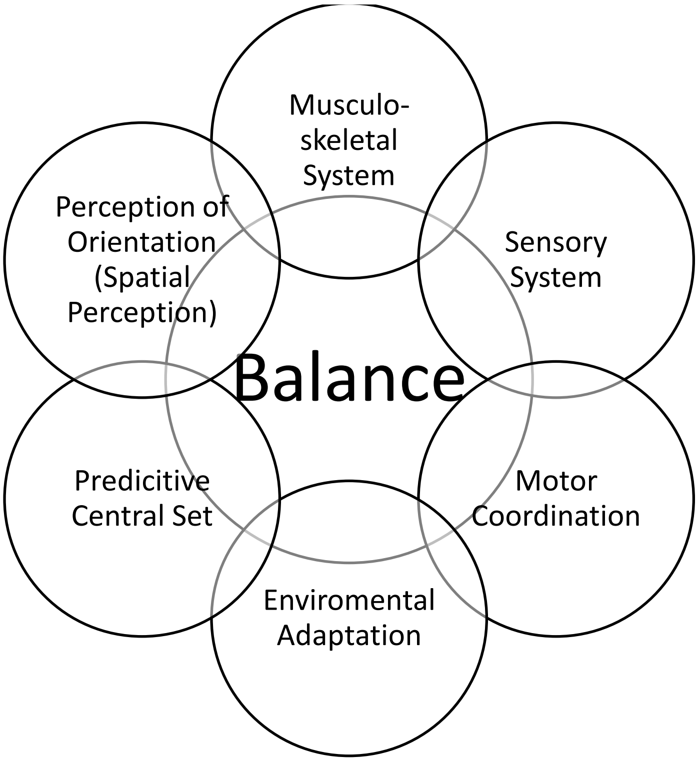

Figure 3.2 *Schematic overview of physiological factors related to balance and stability. Obtained from (Horak, 1991).*

The musculoskeletal system must possess adequate strength and range of motion to control the gravitational and internal forces it encounters. This system gives humans the ability to move and provides form, support, stability, and movement to the body (Dahl & Rinvik, 2010).

The Sensory System is a part of the nervous system responsible for processing sensory information. It consists of sensory receptors, neural pathways, and parts of the brain involved in sensory perception (Dahl & Rinvik, 2010). Postural control is a complex motor skill based on interaction of dynamic sensorimotor processes, where these senses are transducers from the physical world to the realm of the mind. The information from the sensory system is interpreted and a perception of the world around us is created. Sensory input of balance come from four main sources; (1) The vestibular system (motion, equilibrium, spatial orientation), (2) visual system (sight), (3) proprioception (joint and muscle sensors) and (4) mechanoreceptors (pressure, distortion) (Dahl & Rinvik, 2010). Damage to different systems underlying postural control results in different, context-specific instabilities (Winter, 1995). The details regarding how these mechanisms function will not be addressed here.

Motor Coordination is the combination of body movements created with the kinematic and kinetic parameters that result in intended actions. When subsequent parts of the same movement or the movements of several limbs or body parts are combined in a manner that is well timed, smooth, and efficient with respect to the intended goal, motor coordination is achieved. When a person is standing still with a fixed BOS or sitting down on a chair it is often referred as “static balance” because the BOS is not changing. However, this term can be misleading, as postural control even in quiet stance is quite dynamic (Shumway-Cook & Woollacott, 2007). A number of factors contribute to our stability in this situation. Alignment of the posture can be a decisive factor. The ideal alignment in quiet stance, requiring minimal muscular effort to sustain the vertical position, is when the vertical vector (COP) goes through the mass centre and hit the BOS (Shumway-Cook & Woollacott, 2007).

Ankle and hip strategies have been described as movement patterns used to recover stability following displacement of the COM in the sagittal plane, when the BOS is fixed (Shumway-Cook & Woollacott, 2007). However, when stepping is allowed discrete strategies are usually not observed during balance recovery under normal slip conditions; a continuum of movements raging from ankle through hip motion is rather shown. The postural movement strategies during static and dynamic balance are used in both feedback and feedforward control mode to maintain equilibrium in a number of circumstances. Postural control that occurs in response to sensory feedback such as visual, vestibular or somatosensory after an external perturbation refers to feedback control (Buchanan & Horak, 2001). For example (1) when the support surface moves in response to external disturbances to equilibrium, and (2) tripping or slipping during gait in response to unexpected disruptions to the gait cycle (Shumway-Cook & Woollacott, 2007). Feedforward control is referred to as postural responses that are made in anticipation of a voluntary movement in order to maintain stability, if the voluntary movement is potentially destabilizing (Finley, Dhaher, & Perreault, 2009). Examples can be (1) prior to a voluntary movement that is potentially destabilizing where feedforward control is used to prevent a disturbance to the system. (2) During volitional COM movements in stance.

Predictive central set or just central set is closely related to motor coordination. Central set is the nervous systems ability to prepare the motor system for upcoming sensory information and prepare the sensory system for upcoming movements (Horak, 1991). The central set is highly based on prior experience and can for example be used to predict the weight of an object and the dynamics of our limbs in complex, bilateral tasks, like perform tricks with a soccer ball (Horak, 1991).

Perception of Orientation – our perception of body position in space is described as the ability to orient the body parts with respect to gravity, the support surface, visual surround and internal references (Horak, 2006). This awareness automatically alters how the body is oriented in space, depending on the context and the task, given that the nervous system works optimally. For example, orientation of the body perpendicular to the support surface of a given person may function well until the support surface tilts, and then the person orient their posture to gravity (Horak, 2006; Riccio, Martin, & Stoffregen, 1992). *Environmental adaptation* relies severely on the availability of relevant sensory information of the given task. A normal functional nervous system adapts to sudden changes of conditions by gradually changing the movement strategy, taken into account prior experience with environmental conditions, and continuously evaluating the relative success of its actions (Horak, 1991).

3.2 Movement strategies

Ankle strategy and its related muscle synergy were among the first patterns for controlling upright sway to be identified. The term “ankle strategy” was defined for a strategy that restores the COM to a position of stability through body movement centred primarily around the ankle joints (Runge, Shupert, Horak, & Zajac, 1999). Another strategy that can contribute to postural control is the hip strategy, which restores the COM to a position of stability through body movement centred primarily around the hip (Horak, 2006). In Figure 3.3, two postural strategies for controlling the COM in response to backward perturbations of the support surface are shown. The two postural strategies are characterized by different joint motions and muscle activation patterns. For example, when creating a backward sway the ankle strategy (figure 3.3A) activate muscles related to the ankle on the posterior side of the body, and in the hip strategy (figure 3.3B), the hip goes from an extended to a flexed position and muscles related to the hip on the anterior side of the body are activated. However the hip strategy has a longer latency in the muscle activation than in the ankle strategy (Ting, 2007). The two strategies can often be observed as a mix in most postural responses (Runge et al., 1999; Creath, Kiemel, Horak, Peterka, & Jeka, 2005). In forward perturbation (backward sway) when distinguishing ankle strategy the anterior side of the body muscle synergy is activated (Shumway-Cook & Woollacott, 2007). The ankle movement strategy described above appears to be used most commonly in situations in which the perturbation to equilibrium is small and the support surface is firm, while the hip strategy is used to restore equilibrium in response to larger, faster perturbations, or when the support surface is compliant or smaller than the feet (Horak & Nashner, 1986).

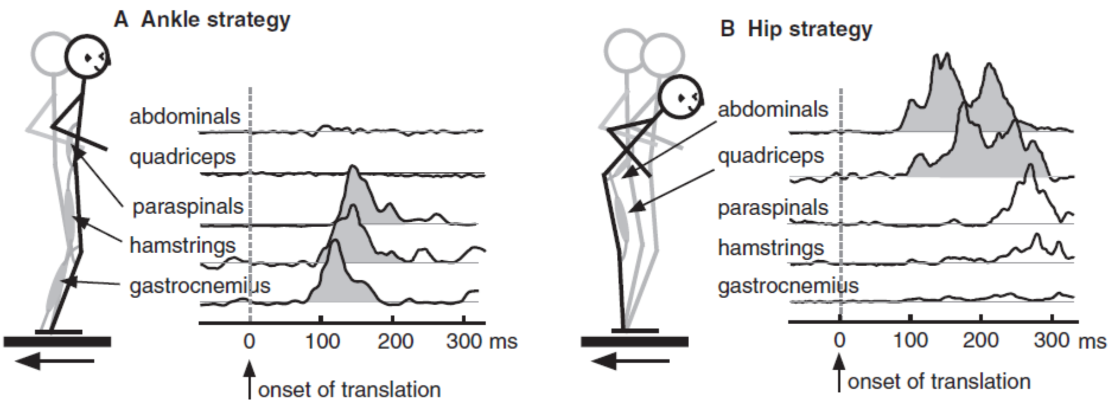

Figure 3.3 *Two postural strategies, ankle (A) and hip (B), for controlling the COM in response to backward perturbations of the support surface. Obtained from (Ting, 2007).*

Co-contraction is defined as simultaneous contraction of agonist and antagonist muscles acting around a joint to hold a position. The co-contraction increases static stiffness of the joint, leading to joint compression (Magee, Zachazewski, & Quillen, 2007). It has been shown there is a decrease in co-contraction level associated with the learning process of a new skill or activity, where the high level of co-contraction in the beginning of the learning process is a strategy to simplify the complexity of the task and increase stability (da Fonseca et al., 2004). Several studies have shown that the amount of co-contraction decreases with practice, in addition it has been shown that co-contraction increases with load instability and joint stiffness and damping increase with co-contraction (Milner, 2002). A related topic to co-contraction is the degrees of freedom, and a commonly discussed topic is Bernstein’s (1967) theory of freezing and releasing degrees of freedom when learning a new task or skill. In a study of change in the organization of degrees of freedom with learning on a ski-simulator apparatus no significant changes in the distribution of degrees of freedom was found, and it was suggested that there is not necessarily an isomorphism between dimension of control and the dimension of the task constraint (Hong & Newell, 2006). Newell & Vaillancourt (2001) suggested that the organization of the mechanical degrees of freedom can either increase or decrease according to the composition and complexity of the action.

Adapting motor strategies

The ability to modify behaviour in response to new task demands is called adaptation. In response to new demands under changing task and environmental conditions postural control requires that we modify how we move. Studies have suggested that subjects without neural pathology can shift relatively quickly from one postural movement strategy to another; Horak & Nashner (1986) asked a group of subjects to stand on a narrow beam while experiencing anterior- posterior platform displacements. In this study most subjects shifted from an ankle to a hip strategy within 5 to 15 trials. When the subjects returned to a normal support surface, they shifted back to an ankle strategy within 6 trials. Complex combinations of the pure strategies were observed during the transition from one strategy to the next. By examining the responses of adults to repeated translational platform movements, Woollacott, von, & Rosblad (1988) found that with repeated exposure to the movement, the subjects swayed less and showed smaller amplitude to the postural responses. Thus, research has shown that we are constantly modulating the amplitude of our postural responses, fine-tuning them to the context to optimize response efficiency. It has been shown that adults increase their reliance on visual input when learning a new balance task, however, in a study conducted by Lee & Lishman, (1975) it appeared that as the task became more automatic, the relative importance of visual inputs for postural control decreased and the reliance on somatosensory input increased. The same scenario have been shown by Mulder, Berndt, Pauwels & Nienhuis (1993), where they suggested that adults recovering from a neurologic lesion also rely predominantly on vision during the early part of the recovery process. As motor skills, including postural control, are regained, patients become less reliant on vision, and are more able to use somatosensory inputs.

3.3 Principal Component Analysis

Human postural control is facilitated through postural movements such as ankle-, hip-, or multi-joint strategies (Winter, 1995). In recent years, advances in data acquisition have led to an enormous increase in number and length of empirical signals. Hence the analysis of multi-dimensional signals has become a central issue across disciplines highlighting the crucial question of how to define relevant features. Principal component analysis (PCA) applied to kinematic marker data offers one approach for studying the structure of postural movements by identifying and quantifying correlated segment motion (Federolf, Reid, Gilgien, Haugen,

& Smith, 2012). PCA is a mathematical method to determine the direction of the largest variability in high-dimensional data sets (Daffertshofer, Lamoth, Meijer, & Beek, 2004). This is an analysis approach that has gained more interest in biomechanical research field during recent years (Daffertshofer et al., 2004; Epifanio, Avila, Page, & Atienza, 2008). PCA was however already invented in 1901 by Karl Pearson as an analogue of the principal axes theorem in mechanics (Pearson, 1901). Thirty years later PCA was independently developed and named by Harold Hotelling (Hotelling, 1933). The method is most frequently used as a tool in exploratory data analysis and for making predictive models. In this project PCA is used as a mathematical method to determine the direction of the largest variability in high-dimensional data sets (Daffertshofer et al., 2004).

In order to prepare for the PCA calculations we need to interpreted the spatial coordinates as a posture vector P(*t*) in a x-dimensional vector space (posture space) similarly as described by (Troje, 2002). For example, if we have 10 reference point coordinates this space would be spanned by all 10 reference point coordinates:

$$\overrightarrow{P(t)} = \{m_{1,x}(t), m_{1,y}(t), m_{1,z}(t), m_{2,x}(t)..m_{10,z}(t)\}$$

where m_i with $i = 1\ldots10$ refer to the marker number and *t* refers to the time index of the selected video frame. At each measured time point a subject has a specific posture that corresponds to a specific vector in the posture space (vector space). The posture and the vector representing a subjects’ posture in vector space are changing as the subject moves. The movements of a subject are therefore represented by the variability of the posture vectors in posture space. A *mean posture* can be calculated for each subject:

$$\overrightarrow{P_{mean}} = mean_{all\ time\ points}\overrightarrow{(P(t))}$$

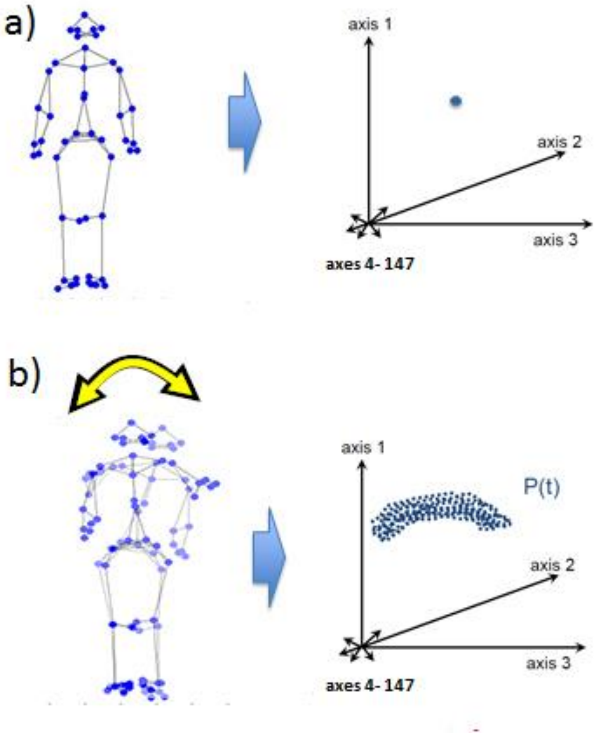

Figure 3.4 *Representation of a subject with 49 markers and the (a) corresponding posture vector in the vector space. As the subject (b) moves a new posture vector appears for each time frame and we get a cloud of points represented by the posture vectors.*

The calculation steps for PCA can be dived into four steps where (1) is removal of the mean, (2) calculation of the covariance matrix of the data, (3) determination of the eigenvalues and eigenvectors of the covariance matrix; and (4) transform the original data onto a coordinate system spanned by the eigenvectors of the covariance matrix (Federolf et al., 2012a).

In the application of PCA on the posture vectors the removal of the mean in this study represents the subtraction of the mean posture $\overrightarrow{P_{mean}}$. This way, only changes in posture, that is, only relative movements are analysed. The eigenvector of the covariance matrix with the largest eigenvalue points is in the direction of the largest variance of the data set, while the second eigenvector represents the direction of the second largest movement in the subspace perpendicular to the largest movement and so on. In this study the largest variance of the data set represents the direction of the largest movement of the subject and the second one represents the second largest and so on. The eigenvectors are also called “principal component vectors” $\overrightarrow{(PC_k)}$ and are ordered according to the amount of variability they represent. The eigenvalues (EV_k) quantify the amount of variability in the direction of the associated principal component vector. The eigenvalues can be represented as absolute values or relative values. To represent the eigenvalues as relative values they have to be normalized.

This can be done by dividing the covariance matrix by its trace. In the example given above the eigenvalues could represent the relative variability of posture vectors (in %) in the direction of the corresponding eigenvector relative to the variability in the entire data set. The transformation of the original 30-dimensional posture vectors onto a coordinate system spanned by the principal components

$$\overrightarrow{P(t)} = \overrightarrow{P_{mean}} + \sum_{k=1}^{30} C_k(t)\overrightarrow{PC_k}$$

would be facilitated by projecting each posture vector onto the principal components yielding the coefficients C_k:

$$C_k(t) = \overrightarrow{P(t)} \cdot \overrightarrow{PC_k}$$

The information in the original data set can be highly redundant, hence it is not necessary to consider all principal component vectors. If the eigenvalue (EV_k) of a principal component (PC_k) is small, then the movements of the subject in the direction of the associated PC_k is small and hence do not add substantial information about the movements of a subject. Because of this, the data can be represented with a given level of accuracy by predefining a threshold and only consider those PC_k whose EV_k exceed the threshold. For instance Federolf et al. (2012a) showed that the first four and eight PC_k together were responsible for 95.5% and 99.3% respectively of the entire variability of the data set in alpine skiing technique, and Troje (2002) showed that the first four PC_k together covered 98% of the variance in human gait.

4. Materials and Methods

4.1 Study design

This longitudinal study was based upon the data collected for this specific project in fall 2012.

4.2 Participants

Thirteen volunteers met the inclusion criteria and were admitted into the study. The study was approved by an institutional ethics review board and all subjects provided informed written consent prior to being participating in the study. Recruitment was carried out by sending e-mail to students and personal appearance. Out of the 13 subjects 2 dropped out in the course of their test week because they became sick (1 subject) or because they suffered an injury (1 subject) – in their leisure time, not related to the study – that could potentially affect how they balanced and were therefore excluded. 11 subjects completed the full study protocol. An overview of their characteristics is presented in table 4.1.

Table 4.1 *Subject characteristics*

		Mean	**SD**	**Range**
N = 11	Age (yrs)	25,1	1,7	23 – 28
	Height (m)	1,8	0,07	1,69 - 1,92
	Body mass (kg)	77,2	5,8	67,0 - 86,9
	BMI	23,5	1,3	21,6 - 25,6

4.3 Test procedures

The testing consisted of five consecutive testing days including anthropometrical measures at day one. The same tests were conducted each day, with a total duration of approximately one hour including the preparation of the subject. All the tests were performed in the biomechanics laboratory at the Norwegian School of Sport Sciences. Before the tests begun the subjects filled out a questionnaire regarding general information, injuries, training background and health (appendix 2).

4.4 Test protocol

Five balance tests were conducted per day for all the five consecutive testing days. During the tests, the subjects wore nothing but underwear or tight sport shorts. All tests were performed barefoot. A brief overview of the protocol for one testing day is shown in table 4.2.

Table 4.2 *Protocol overview.*

Task	Duration	Remarks
Anthropometric data	5 min	Day one only
Preparation of subject	20 min	Placement of reflective markers
Static calibration	5 min	Three different calibration recordings of subject
Wobble board calibration	2 min	Calibration of marker thresholds on the wobble board
Balance test #1	2 min + 4 min break	Quiet stance on the wobble board
Balance test #2	2 min + 4 min break	Quiet stance on the wobble board
Balance test #3	2 min + 4 min break	Quiet stance on the wobble board
Balance test #4	2 min + 4 min break	Quiet stance on the wobble board
Balance test #5	2 min + 4 min break	Quiet stance on the wobble board
Marker removal	10 min	Remove equipment from subject

4.4.1 Test station setup

The testing was performed in a big, well lit room. Each subject was instructed to stand on a wobble board (Return To Fitness Ltd, Norwich, UK), placed in the centre of the recording area, for two minutes. The objective of the subject was to stand as long as possible on the wobble board without its rim touching the ground. The subjects were instructed, that if the wobble board did touch the ground, they should restore balance as soon as possible and continue with the exercise. Each trial started with the subject placing their feet on the wobble board according to markings taped onto the wobble board. The subjects then stood on the board with its posterior rim in contact with the ground. When the subject was ready, recording was started and the subject was told to begin the task. When two minutes had past, the recording stopped and the subject was allowed to step off the wobble board. No instructions were given regarding posture, eye focus or arm placement. Feedback regarding the time during testing was not given. All attempts were accepted unless the subject left or fell off the wobble board during trial - which occurred one time only. If that was the case a new trial was performed. Four to six minutes break was given in between each trial.

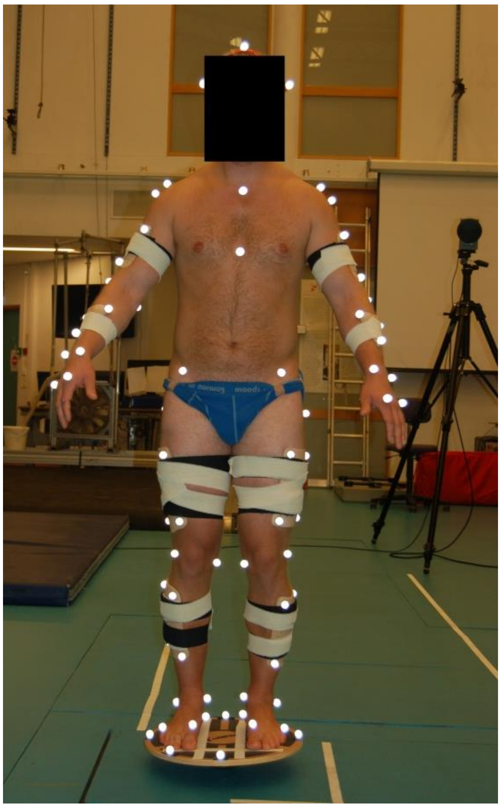
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Figure 4.1 *A subject balancing on the wobble board.*

Marker placement

Forty-nine, 2 cm reflective markers were attached to specific palpable anatomical landmarks on each subject (table 4.3, figure 4.2). In addition five reflective markers were placed on the edge of the wobble board on the top, bottom, left side, right side and upper right side, where the upper right side marker defined the direction of the wobble board (table 4.4, figure 4.3). First, in the procedure, the palpable anatomical landmarks were identified as described in table 4.3. Then the area was shaved if necessary, cleaned with isopropanol and marked with a waterproof pen. Finally the markers were attached to the subject's body with double sided tape. Clothing covering anatomical landmarks was removed and kept in place by Strappal® adhesive sport tape.

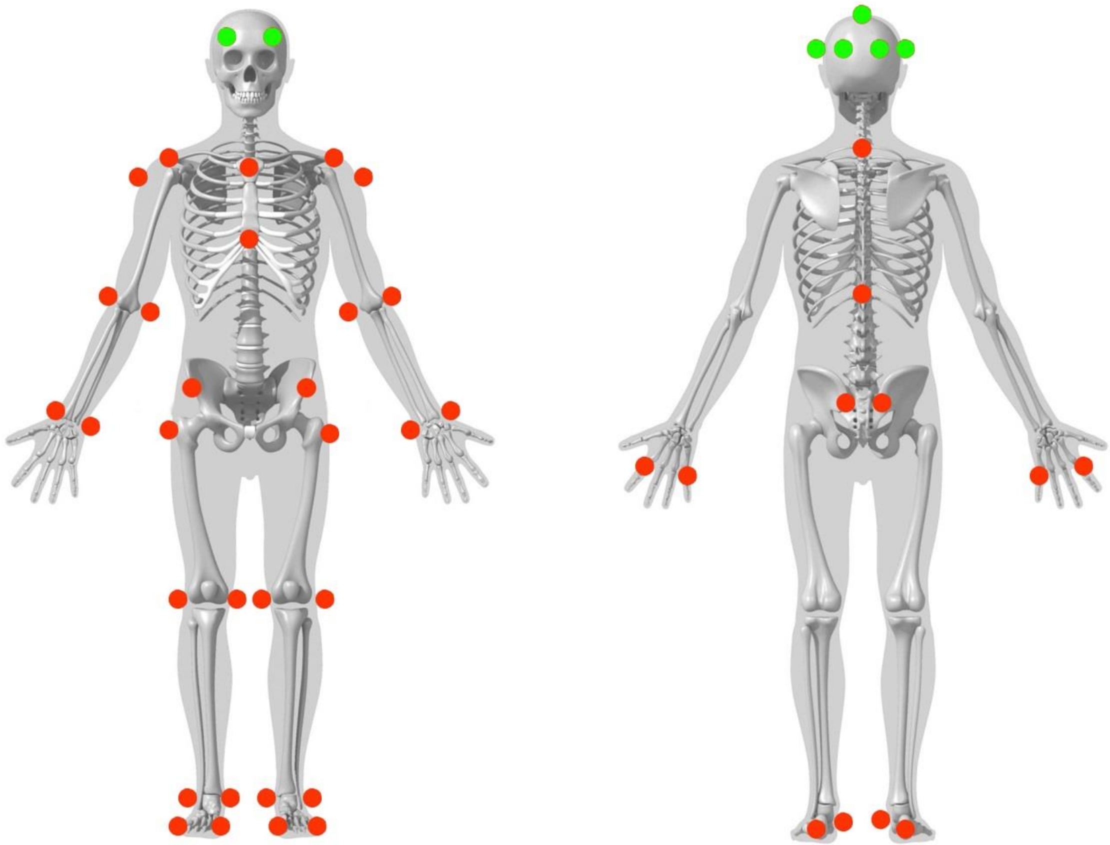

Figure 4.2 *Placement of the 49 markers. Circles marked in green are attached to a helmet, circles marked in red are single markers placed directly on the skin.*

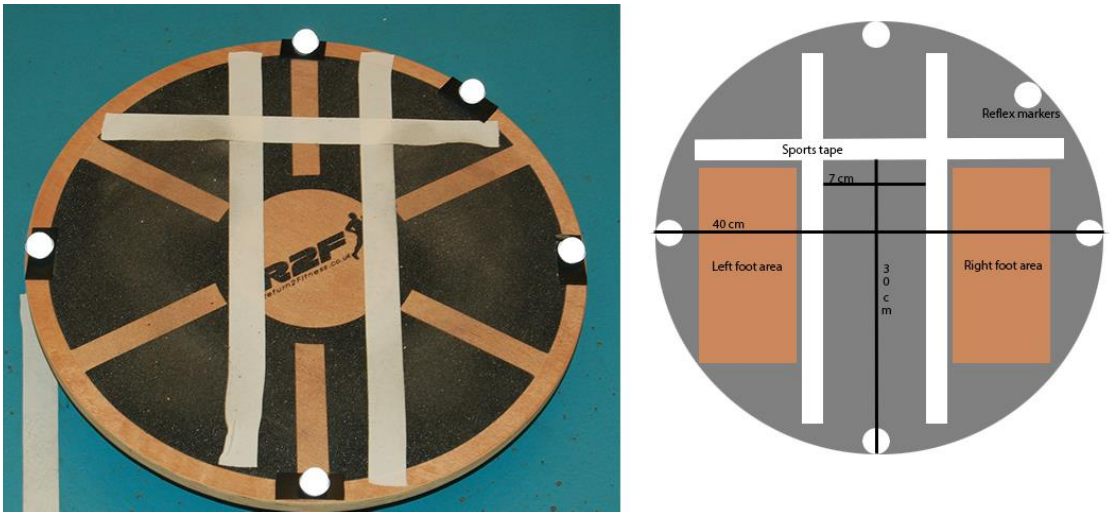

Figure 4.3 *Left: picture of wobble board. Right: Schematic drawing of wobble board.*

Table 4.3 *Marker placement with description.*

Number	**Segment**	**Marker**	**Papable landmark**
1	Foot	RCA	Right posterior calcaneus
2	Foot	LCA	Left posterior calcaneus
3	Foot	RST	Right sustentaculum tali
4	Foot	LST	Left sustentaculum tali
5	Foot	RVMH	Right 5th metatarsal head
6	Foot	LVHM	Left 5th metatarsal head
7	Foot	RFM1	Right 1st metatarsal head
8	Foot	LFM1	Left 1st metatarsal head
9	Shank	RFAL	Right lateral malleolus
10	Shank	LFAL	Left lateral malleolus
11	Shank	RTAM	Right medial malleolus
12	Shank	LTAM	Left medial malleolus
13	Thigh	RFT	Right greater trochanter
14	Thigh	LFT	Left greater trochanter
15	Thigh	RFLE	Right lateral condyle
16	Thigh	LFLE	Left lateral condyle
17	Thigh	RFME	Right medial condyle
18	Thigh	LFME	Left medial condyle
19	Pelvis	RIAS	Right anterior superior iliac spine
20	Pelvis	LIAS	Left anterior superior iliac spine
21	Pelvis	RIPS	Right posterior superior iliac spine
22	Pelvis	LIPS	Left posterior superior iliac spine
23	Thorax	CV7	Spinous process C7
24	Thorax	TV10	Spinous process T10
25	Thorax	SNJ	Superior jugular notch
26	Thorax	SXS	Sternum xiphisternal joint
27	Head	RAH	Right anterior head
28	Head	LAH	Left anterior head
29	Head	RLH	Right lateral head
30	Head	LLH	Left lateral head
31	Head	RPH	Right posterior head
32	Head	LPH	Left posterior head
33	Head	SAS	Aphex skull
34	Clavicle	RAC	Right most dorsal point of acromioclavicular joint
35	Clavicle	LAC	Left most dorsal point of acromioclavicular joint
36	Upper arm	RSHO	Right rotation center shoulder joint
37	Upper arm	LSHO	Left rotation center shoulder joint
38	Upper arm	RHLE	Right humeral lateral epicondyle
39	Upper arm	LHLE	Left humeral lateral epicondyle
40	Upper arm	RHME	Right humeral medial epicondyle
41	Upper arm	LHME	Left humeral medial epicondyle
42	Lower arm	RRSP	Right radial styloid process
43	Lower arm	LRSP	Left radial styloid process
44	Lower arm	RUSP	Right ulnar styloid process

45	Lower arm	LUSP	Left ulnar styloid process
46	Hand	RHL5	Right head 5th metacarpal – dorsal surface
47	Hand	LHL5	Left head 5th metacarpal – dorsal surface
48	Hand	RHM2	Right head 2nd metacarpal – dorsal surface
49	Hand	LHM2	Left head 2nd metacarpal – dorsal surface

Table 4.4 *Marker placement with description for wobble board.*

Number	Marker	Landmark
1	WBA	Wobble board posterior
2	WBP	Wobble board anterior
3	WBLL	Wobble board left lateral
4	WBRL	Wobble board right lateral
5	WBRA	Wobble board right anterior

Static recording

Prior to the balance tests three static recordings of the subject were made: (1) Standing in anatomical position, (2) anatomical position with 90º in elbow joint and palms up, and (3) anatomical position with 90º in elbow joint and palms down, facing X direction of the Global Coordinate System (GCS) (figure 4.4). The static recording was conducted to derive the anatomical axis of the segments in order to establish the three dimensional relationship between the reflective markers and the anatomical axis of each segment.

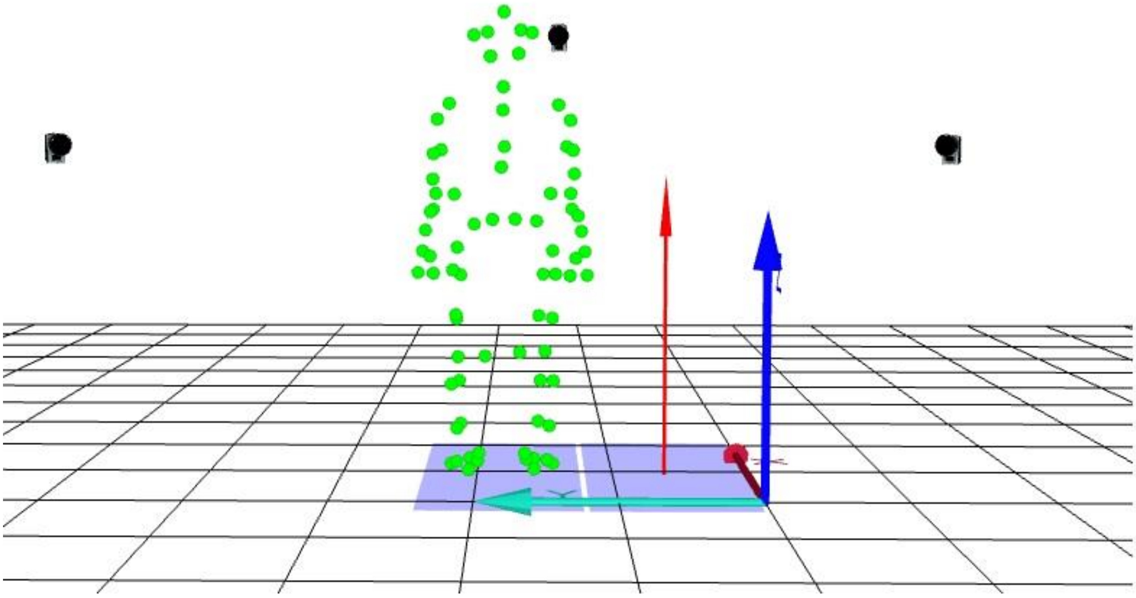

Figure 4.4 *Image of a subject doing a static recording in Qualisys Track Manager.*

Cinematographical System

The laboratory setup consisted of a force plate built into the floor on an indoor court floor surrounded by sixteen cameras organized in an optical tracking system (ProReflex, Qualisys INC Gothenburg, Sweden). The cameras were emitting infrared light at a recording frequency of 480Hz, and were recording the reflections from the reflective markers placed on the subject and the wobble board. Optimal positioning of the cameras was sought to achieve as high precision of the marker placement as possible. Marker placement precision is dependent of the number of cameras the marker is visible in, and the intersection angle of the recording cameras (90º optimal). Figure 4.5 displays the laboratory camera setup.

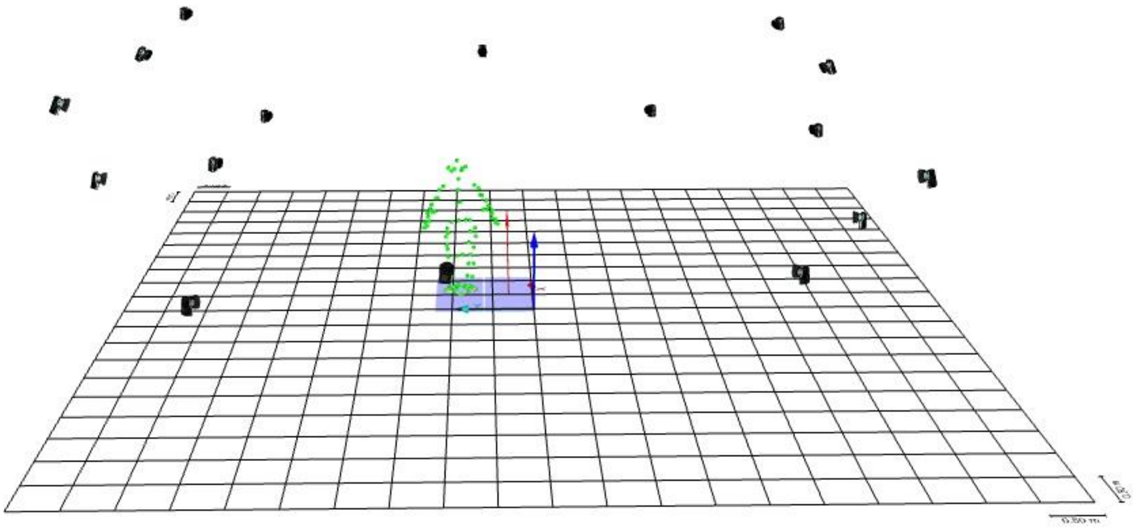

Figure 4.5 *Camera setup for the optical tracking system. Each thick black dot represents a camera position.*

The calibration procedure to correct for the lens distortion, and to define the recording area/grid, was conducted according to the recommendations of the manufacturer of the system (Qualisys INC Gothenburg, Sweden). The procedure was a two-stage calibration. First, a physical frame with four reflective markers attached to it was placed onto/around a build in force platform in the centre of the intended recording area/grid. Secondly, a calibration wand (1499.3 mm long), with one reflective marker in each end, was moved around in the area/grid by one tester for 45 seconds. This calibrated the recording area to a global coordinate system (GCS) with the X-axis defined as positive anterior-posterior direction, Z-axis vertically and Y-axis perpendicular to the X-axis in a right medio-lateral orientation. This calibration procedure was performed previous to the testing of each subject. Only threshold values with an average residual less than 1.0 mm and a standard deviation of wand length (standard deviation of the distance between the two outermost markers on the wand over all frames in which the markers could be identified) less than 1.0 mm was accepted.

4.4.2 Signal treatment

Marker recordings

When the data recording was complete, the Qtrack software (Version 2.7, Qualisys AB, Gothenburg, Sweden) provided calculation of the 3D trajectories of each marker. To complete the 3D trajectory calculation of each marker in the Qtrack software (Version 2.7, Qualisys AB, Gothenburg, Sweden) it had to be manually identified according to the previously described marker arrangement.

4.5 3D motion analysis

Global Coordinate System

The GCS provided the reference system used to describe orientation and movement of the each segment in relation to each other. The GCS system was defined by the calibration as previously described in the laboratory setup.

Mathematical model and calculations

All the following estimations and calculations were executed by a MATLAB® 2011b script written by Peter Federolf and Even Granerud for use in this project. Federolf coded the calculation of principal movements using PCA and Granerud coded the calculation of the balance score based on the vertical displacement of the wobble board markers.

All trials were visually inspected during data recording and during post-processing. From each trial, a period of 90 seconds, from second 15 to 105, was selected for further analysis to avoid movements due to stepping into or out of the balance task. In some trials a brief loss of marker positions appeared and therefore gaps had to be filled by using a novel gap-filling routine as described by Federolf (in press). At any given time in the analysis period, a subject's posture was quantified by the 49 3D-marker coordinates. These 147 spatial coordinates were interpreted as an 147-dimensional posture vector $\boldsymbol{p}(t_i)$. In each trial 43,200 posture vectors were collected (90 seconds at 480 Hz measurement frequency) quantifying the entirety of the subject's movement during the analysed period. The following description is based on the description of the data analysis procedure of (Federolf, Roos, & Nigg, 2013). A normalization technique that allowed combining the posture vectors of different subjects, such that universal principal movements could be calculated was conducted on the data set. This normalization technique was executed to retain the variability between posture vectors created from postural movements in the input matrix for the PCA, while minimizing those differences between posture vectors that stemmed from anthropometric differences between subjects. The normalization technique was achieved in three steps: (1) A mean posture vector, p_{mean}, was calculated for each trial and subtracted from all posture vectors of this trial. (2) The vector norm, $d(t_i)$, of these centred posture vectors was calculated. (3) All centred posture vectors were divided by the mean vector norm, d_{mean}, calculated for the entire trial.

$$p_{norm}(t_i) = (p(t_i) - p_{mean})/d_{mean}$$

The normalized and centred posture vectors $p_{norom}(t_i)$ of all subjects were then assembled into one input matrix for the PCA, i.e. for each of the 25 trials one 475,200x147-input matrix was obtained (480Hz x 90seconds x 11 subjects).

The PCA is a mathematical procedure that uses orthogonal transformation to convert a set of observations of possibly correlated variables into a set of values of linearly uncorrelated variables called principal components or eigenvectors. The principal component vectors PC_j, indicated the direction of the largest variance of the posture vectors within the 147-dimentional posture space. For each PC_j there was an associated eigenvalue EV_j quantifying the variance in the direction of that PC_j. A coefficient $c_j(t_i)$ quantified the progression of each one-dimensional principal movement, which was determined by projecting the posture vectors $p(t)$ onto the principal component PC_j. Time series formed by the coefficients $c_j(t_i)$ allowed a quantitative analysis of the principal movements carried out by a subject during a postural control task.

$$c_j(t_i) = p_{norm}(t_j) \cdot PC_j$$

An approach allowing to visualize the principal movement with stick figures or animations was achieved by projecting each principal movement back into the original posture space and rescinding the normalization yielded posture vectors, $PM_j(t_i)$,

$$PM_j(t_i) = p_{mean} + a_j \cdot d_{mean} \cdot c_j(t_i) \cdot PC_j$$

This way representing a subject’s principal movement components in the original marker coordinates, where indices i, j refer to the time frame (i = 1...43,200) and the number of the principal component (j = 1...147), respectively. The amplification factor a_j introduced in this equation relieved a visual assessment of the principal movement.

Normalized eigenvalues were used as variables quantifying the internal structure of the principal movements. These normalized eigenvalues, EV_j, was normalized by dividing each EV_j by the sum of all EV_j. The EV_j quantify how much the corresponding PM_j contributed to the entirety of postural movements observed inn all subjects. To quantify the contribution of each PM_j to the postural movements in an individual subject, a normalized variance, ${\sigma^2}_j$, from the coefficient-time series $c_j(t)$ was calculated. In comparison to the eigenvalues, the ${\sigma^2}_j$ were normalized by dividing them by the sum of all ${\sigma^2}_j$ of a subject. A cumulative normalized variance, $\sum {\sigma^2}_j$, was calculated as a measure of how much of the entire variance observed in a subject's trial was represented by a given number of principal movements. That is, how many PM_j needed to cover a predefined fraction of variance in the data:

$$\sum {\sigma^2}_j = \sum_{k=1}^{j} \sigma_k^2$$

To determine the linear relationship between how the subjects structured their postural movement PM_k related to balance score and trial number a Pearson's correlation coefficient was calculated.

A balance score (BS) was calculated for each trial to quantify the balance performance of the subjects. This balance score was based on the vertical displacement of four markers placed on the edge of the wobble board. The fifth (upper right side) marker was not taken into account because this marker was for defining the direction of the wobble board only. Only the vertical displacement of the markers was accounted for. This was done because it often happened that the wobble board slightly rotated during phases on instability. Large variability in X- and Y-coordinates could therefore occur as a result of such a rotation, however, this would not indicate an instability of the subject. The balance performance was then calculated as the standard deviation of the mean for all time frames of each marker:

$$BS = \sum_{m=1}^{4} \frac{1}{N-1} \sqrt{\sum_{i=1}^{N} \left(Z_{i,m} - \bar{Z}_m\right)^2}$$

where Z is the vertical coordinate of the marker m and N is the number of observations during a trial, i.e. N = duration of the trial • measurement frequency.

4.6 Statistics

The statistical analysis was calculated using SPSS (Version 19, SPSS Inc., Chicago, IL, USA). To investigate within subject development of the 25 trials repeated measures ANOVA was used, with confidence interval of 95% to judge statistical significance. A Sidak correction was used to counteract the problem of multiple comparisons. Pearson’s correlation coefficient was used to measure the strength and direction of the linear dependence between variables within individual subjects.

5. Results

5.1 Balance Performance

Balance performance on the wobble board improved the most over the first 2-3 test days. Overall the balance score decreased from 52.1±11.0 mm in the first trial to levels below 34.2±6.1 mm in all trials of the 4th and 5th day (mean±stdev). The overall improvement in balance performance was significant ($F(1,24) = 11.17$, $p<0.007$). Individual results showed that ten subjects had a significant decline in wobble board movement while one subject did not. Figure 5.1 show a graphical illustration of the balance performance.

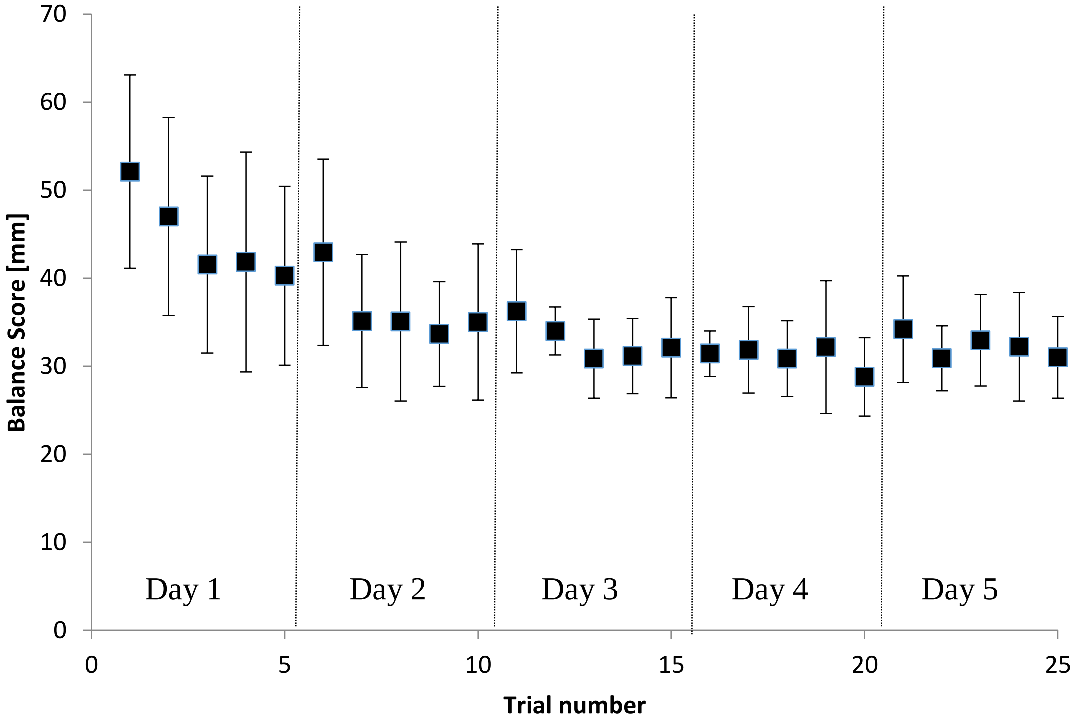

Figure 5.1 *The balance score for all subjects for all trials (mean±stdev). The horizontal axe is trial number, and the vertical axe is the displacement of the board in mm.*

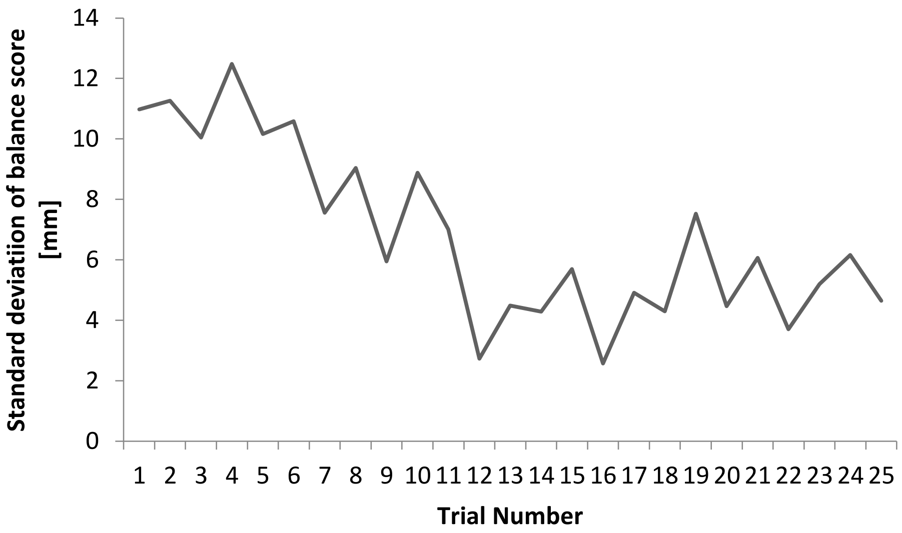

Figure 5.2 *The development of the standard deviation of the balance score through the 25 trials for the whole group.*

Figure 5.2 shows that the standard deviation of the balance score also decreased by practice. The lowest standard deviation was on trial 12 (day 3) and trial 16 (day 4). The results showed somewhat various values on day 4 and 5.

5.2 Principal Movements

The eigenvalues of all subjects distributed by all trials (mean) for the first 15 PM_k are shown in figure 5.3. Stick figure representations of the different PM_k are shown in figure 5.4. These figures give a visual impression as a moving picture of the different movement patterns distributed by the PM_k. The first ten and fifteen PM_k together were responsible for 90.0% and 95.3% of the variance in the posture vectors respectively. Stick-figure representations of the resultant PMs offer a visual impression of the characteristics of each PM and facilitate a qualitative interpretation (figure 5.4). PM_1 represent 26.5% of the original motion and accounts for the largest part of the motion. The motion strategy underlying this PM is an anterior-posterior sway anchored in the ankles and hip, resulting in anterior-posterior control of the wobble board. PM_2 represents 23.7% of the original motion and accounts for the second largest part of the motion. Motion strategies underlying PM_2 are lateral movement originating from the hip and ankle, causing a lateral control of the wobble board. PM_3 represents 12.2% of the original motion and accounts for the third largest part of the motion. In this PM the motion is limited to the ankle joints in a plantar/-dorsal movement, causing an anterior/-posterior movement of the wobble board. PM_4 represent 7.8% of the whole motion and controls anterior/-posterior movement of arm segments, which have limited effect on the wobble board. PM_5 represent 6.2% of the whole motion and controls lateral movement of the shoulder bow and arm segments, causing lateral control of the wobble board. PM_6 represents 4.6% of the whole motion and represents a combination of abduction/-adduction and anterior/-posterior movement of the arm segments. This PM has limited effect on the wobble board control. PM_7 represents 3.0% of the whole motion. This PM lowers and raises the centre of gravity by knee flexion/-extension. PM_8 accounts for 2.9% of the whole motion and consist of upper body rotation around the vertical axis, with limited effect on the wobble board. PM_9 represent 1.8% of the whole motion and consist of abduction and adduction of arm segments, where right and left arm move in the opposite direction of the other. PM_{10} represent 1.3% of the whole motion and consist of rotation around the vertical axis, which is somewhat transferred to the wobble board.

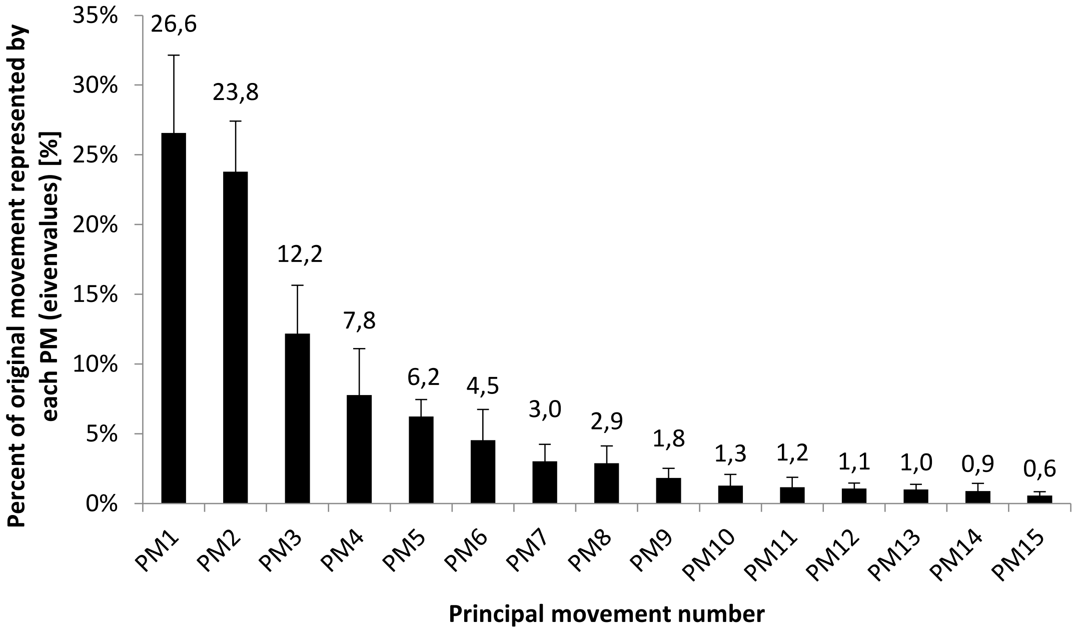

Figure 5.3 *Principal movements (1-15) for all subjects distributed by all trials (mean). Principal movement number 1 represents the highest per cent of the variance of the original movement followed by principal movement number 2 representing the second largest variance, and so on. Error bars represent standard deviation.*

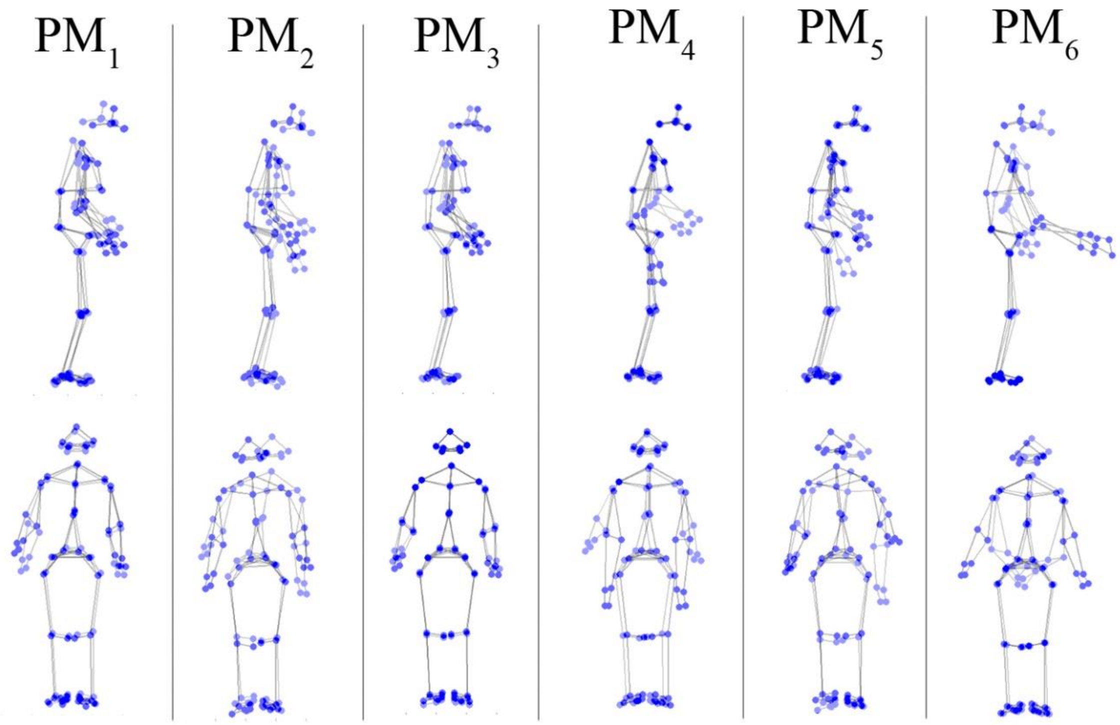

Figure 5.4 *Illustration of stick-figure representation for principal movement 1-6 (Stillpictures from a moving picture).*

Table 5.1 *Correlation coefficient of several variables. PC1 – PC10 represents the principal components from 1 to 10. BS represents balance score. * indicate significance according to table A.2 from Vincent (2012) with p<0.05 giving a threshold value of 0.602.*

		PC1	**PC2**	**PC3**	**PC4**	**PC5**	**PC6**	**PC7**	**PC8**	**PC9**	**PC10**
PC vs BS	**FP01**	0,038	-0,216	0,262	0,094	-0,349	-0,274	-0,395	0,376	0,437	0,112
PC vs trial#		0,102	0,107	-0,259	0,130	0,233	0,204	0,308	-0,372	-0,540	-0,214
PC vs BS	**FP02**	0,078	-0,140	-0,547	-0,008	-0,146	0,411	-0,146	0,147	0,022	0,197
PC vs trial#		0,471	0,032	0,407	0,188	-0,070	-0,243	-0,117	-0,451	0,092	-0,416
PC vs BS	**FP03**	**-0,826***	0,438	-0,168	-0,296	0,339	0,366	0,183	0,307	0,312	0,144
PC vs trial#		**0,704***	-0,484	0,106	0,238	-0,315	-0,212	-0,189	-0,142	-0,205	-0,063
PC vs BS	**FP04**	-0,487	0,287	**0,645***	0,104	-0,041	**-0,722***	0,088	0,251	-0,312	-0,124
PC vs trial#		0,502	-0,064	-0,482	-0,246	-0,102	**0,677***	-0,122	-0,388	0,148	-0,052
PC vs BS	**FP05**	0,266	0,276	0,146	-0,494	-0,520	0,349	-0,353	0,188	-0,191	0,187
PC vs trial#		-0,498	**-0,713***	0,390	0,389	**0,646***	-0,487	**0,629***	-0,033	-0,011	-0,239
PC vs BS	**FP06**	-0,155	-0,430	0,016	-0,203	-0,391	0,228	0,330	0,524	0,461	**0,652***
PC vs trial#		0,115	0,262	0,275	0,044	**0,636***	-0,347	-0,501	-0,369	-0,097	**-0,624***
PC vs BS	**FP07**	0,158	0,128	-0,462	-0,189	-0,034	0,239	-0,233	0,230	0,072	0,393
PC vs trial#		**-0,637***	0,511	0,306	0,597	-0,045	-0,292	-0,432	0,228	0,143	-0,528
PC vs BS	**FP08**	0,071	-0,457	0,045	0,349	-0,453	0,209	0,256	-0,337	-0,319	0,008
PC vs trial#		0,216	0,296	0,086	-0,406	0,284	-0,007	-0,321	0,003	0,121	-0,145
PC vs BS	**FP09**	-0,029	0,284	**-0,672***	0,459	**-0,616***	-0,396	-0,067	0,179	0,335	0,392
PC vs trial#		-0,265	-0,481	**0,785***	0,027	0,460	0,496	0,005	-0,419	**-0,665***	**-0,729***
PC vs BS	**FP10**	-0,362	-0,338	-0,012	0,247	-0,144	-0,197	0,117	0,213	-0,299	0,193
PC vs trial#		0,418	**0,677***	-0,244	-0,393	-0,451	0,267	-0,240	-0,444	0,324	-0,516
PC vs BS	**FP11**	-0,154	-0,006	0,023	-0,104	0,237	-0,133	0,115	-0,108	0,017	0,085
PC vs trial#		-0,268	-0,034	0,096	0,289	-0,372	0,326	0,074	0,069	-0,355	-0,031

Table 5.1 show that there is no consistence of the correlation between the subjects and their associated PCs vs. BS and trial number.

No changes were observed in the structure of the postural movements as quantified by the first 10 PCs: F(1,24)<1.42, p>0.98 in the relative contribution calculated for the first 10 PCs. Figure 5.5 show a comparison of the principal movements (1-15) of trial 1 and 20. These two trials are characterized as the “worst” and the “best” attempt according to balance score, respectively.

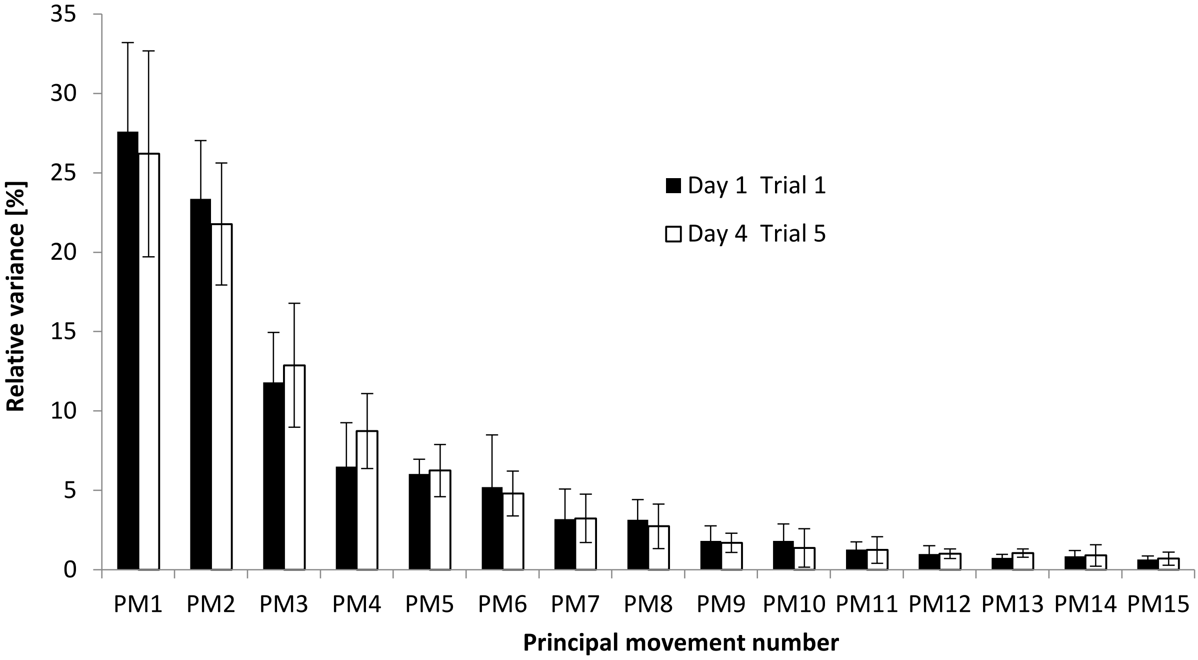

Figure 5.5 *Principal movements 1-15 for day 1, trial 1 (trial 1 – black bar) compared with day 4, trial 5 (trial 20 – white bar). Error bars represent standard deviation.*

6. Discussion

The objective of this study was to explore the development in postural control by using principal component analysis as an analysis tool, as balance performance improves. We found an improvement in balance performance, however the postural control development did not show any significance.

6.1 Balance Performance

Ko et al. (2003) used a moving platform in anterior-posterior direction to record 6 subjects during 30 trials on day one and 10 trials on day two to investigate how they learned to coordinate redundant degrees of freedom in a dynamic balance task. The results showed a significant change in amplitude of anterior-posterior centre of pressure motion as a function of practice; the amplitude of anterior-posterior centre of pressure motion decreased significantly with practice trials, $F(29,145) = 6.09$, $p < 0.0001$. These results corresponds to our findings, in both cases the first 10 trials show the largest improvement in performance. Another study also showed similar results, when balancing on a stabilometer platform trying to keep it in a horizontal position for as long as possible during each 90-s trial (maximum possible deviation to either side being 30 degrees) (Wulf et al., 2003). In addition a “suprapostural” task was conducted which was a wooden tube that the subjects were instructed to hold horizontally with elbows flexed at 90 degrees at abdomen-height. The results showed a significant improvement in balance performance (Root mean square of the deviation of the platform) over 14 trials divided by two days (Wulf et al., 2003). Our study showed that the trials from 1-15 (day 1-3) showed a rapid improvement of balance performance followed by 10 trials (day 4-5) with overall good balance performance. However the fifth day showed somewhat poorer balance performance than day four. This could be, from a subjective point of view, due to lack of concentration on the last day. The subjects were encouraged to perform at their best level, however some subjects seemed to be tired or not challenged enough by the task the last day.

6.2 Principal Component Analysis

To balance on a wobble board is a very complex task. In this study we needed the first ten and fifteen PM_k summarized to cover 90.0% and 95.3% of the variance in the posture vectors respectively. In comparison, when walking on a treadmill for 20 gait cycles (1,400 postures) the first principal component already covers 84% of the overall variance and the first four principal components taken together account for more than 98% of the overall variance (Troje, 2002). Federolf, Tecante, & Nigg (2012) found similar results when investigating walking patterns with normal vs. unstable shoes. Normal shoe condition and unstable shoe condition showed that PM_1 and PM_2 explained 84.2% and 6.6% of the variance in normal shoe condition, respectively, and 84.2% and 6.3% of the variance in unstable shoe condition, respectively. Federolf et al. (2013) found that PM_1 explained 71.7% (mean) of the postural variance in a group performing bipedal stance. Another study quantified the relative contribution of postural variability in alpine skiing, where two whole turning cycles were recorded (volume: 50 m x 10 m x 2 m). The results showed that the first four PM_k together were responsible for 95.5 ± 0.5% of the variance in the posture vectors and the first eight PM_k were responsible for 99.3 ± 0.2% of the variance (Federolf et al., 2012a). When learning the pedalo locomotion task (350 trials over 7 days), results showed a decrease of components over practice, where 3-5 PM were required to accommodate 90% of the variance of the whole-body motion at the end of the final practice session (Chen, Liu, Mayer-Kress, & Newell, 2005). Federolf et al. (2012c) showed the relative contribution of each PM to the entire postural variability of three different conditions in standing; barefoot, athletic casual shoes and unstable shoes. In the barefoot case PM_1 and PM_2 explained 74.4% and 13.7% of the postural variability, respectively, and the three first PM_k explained 93% of the total postural variability. The fact that our exercise was so complex may explain why there was no universal postural strategy that stood out or changed throughout the tests. The idea that the postural movements changes as a subject improve in balance performance, may be wrong. Other reasons, such as spatial and temporal coordination of the muscles or muscle tuning may explain the improvement of controlling the wobble board. However, measurements revealing such information were not conducted in this study.

I has been suggested that freezing redundant degrees of freedom can appear when subjects learn to master a balance task (Ko et al., 2003). With practice the motions of the hip, knee and neck joints became relatively suppressed as indexed by relatively small amplitude of joint angular motion, while the primary compensatory movement occurred at the ankle joint, when maintaining balance on a moving platform sinusoidally translated in the anterior-posterior direction (Ko et al., 2003). It was suggested that this scenario could appear in our study as well. When comparing trial 1 and trial 20 with respect to the PM_k no significant changes appeared. The relative contribution of PM_3 and PM_4 increased by 1.0% and 2.2%, respectively, indicating very small changes in the contribution of ankle (plantar/dorsal) and arms (anterior-posterior) relative to the entire movement strategy. Some subjects showed a more crouched position during early stages of the tests and gained a more upraised posture as the balance performance skills increased, however there was large deviations between subjects in relation to movement solutions of the task.

In 1967 Bernstein identified and described a number of changes that occur associated with learning in humans (and other species) in a range of movement tasks. A generalization was made across these observations and Bernstein suggested a 3-stage model of motor learning where (1) was the initial state reducing (freezing) the number of degrees of freedom at the periphery to a minimum. Then, (2) a gradual lifting (releasing) of all restrictions on the degree of freedom, that is, incorporation in movement coordination of all possible degrees of freedom. And, (3) Utilizing and exploiting the reactive phenomena that arise in movement control (Bernstein, 1967). A generalization of movement strategies when learning a new task is however not commonly accepted, for example it has been suggested that the combined notions of initially freezing and releasing degrees of freedom are constraint and, in particular task dependent, and not general directional stage-like strategies of learning to harness the degrees of freedom (Newell & Vaillancourt, 2001). Anthropometry may also explain the diversity of our results; it has been shown that parameters quantifying the amount of oscillation in stance are strongly dependent on the height (and partly weight) of the subject (Chiari, Rocchi, & Cappello, 2002).

6.3 Limitations

This longitudinal study was limited to investigate the relationship between improvement in balance performance and postural control by kinematic measurement.

The test station setup and the procedures were identically for all the subjects and the testing personnel were the same every time. Knowledge of human anatomy and palpation skills was required in marker placement and proper training of marker placement was conducted by a physiotherapist. The wobble board balance test is easily reproducible, with limited instructions and restrictions for the subjects to relate to. Wobble board training is a common exercise in rehabilitation after injury and is also used elsewhere, therefore subjects who had former experience with this type of exercise were not invited to participate in the study. The wobble board exercise was chosen because it demands a high level of skill to master and the learning effect has a steep curve. The length of the period where the subjects had to stand on a wobble board was relatively long (2 minutes), which could cause an influence on the balance performance due to lack of concentration and fatigue. However, 15 seconds were cut off in the beginning and the end of the recoded tests to eliminate errors.

Principal component analysis can be a valuable tool to detect new sources of variability compared to traditional discrete analyses (Mantovani et al., 2011). Nevertheless PCA has some limitations such as, each source of variability has the same impact on the final score regardless of function and clinical relevance. Such variability whose primary purpose is not to enhance postural control can be breathing, involuntary or voluntary movements to ease fatigue (Federolf et al., 2013). PCA is a non-parametric analysis and the PM_j are a priori mathematical solutions representing correlated, linear changes in the marker set positions, therefore they do not exactly represent movements but linearized versions of them. In this study normalization step comprising of subtraction of the mean posture of each subject and standardise the deviation from the mean posture between subjects was conducted. A computation of principal movement components assembled from several subjects was necessary to compare the structure of the postural movements between subjects, hence eliminating the differences in the movement amplitude. This gives the opportunity to compare relative contributions of a principal movement component in relation to the whole postural movements of a subject. The advantage is that the whole postural movements can be compared between subjects, and the disadvantage is that absolute amplitudes cannot.

6.3.1 Reliability

The fact that this study only included 11 subjects makes it vulnerable to one high or low value due to extreme skills of a subject, instrumental errors and other inaccuracies. There is limited information regarding reliability of wobble board as a testing device, however several studies have used wobble board or different kind of modified wobble- or balance boards in their study (Ogaya et al., 2011; Karime et al., 2012; Fitzgerald et al., 2010). One study did test the reliability and variability using a wobble board very similar to the one used in this study. An instrumented wireless wobble board with a wireless electronic tilt sensor with an angel accuracy of <2% (SMARTwobble board, THETAmetrix, Waterlooville, Hampshire, UK) was used to quantify wobble board performance. Their findings showed that the wobble board used in their study was reliable for measuring balance within a healthy population, and showed a good consistency between different tasks with a good within-day reliability and low variability (Williams & Bentman, in press).

6.3.2 3D motion analysis

Instrumental errors

A very accurate cinematographical system was used in this study, and the source of this error is likely to be very small. Recommendations from Qtrac Capture & view reference manual (ProReflex, Qualisys INC Gothenburg, Sweden) was followed to set up the laboratory. The sixteen cameras were set up with the intention to hit each reflective marker with at least two cameras that were as close to 90º on an optical axis as possible. The distance between the cameras and the subjects were approximately 3-6 meters and the calibration output indicated that the system recorded the reflective markers within one millimetre of actual position. With as many as sixteen cameras the probability of capturing the reflective markers with at least two cameras at 90º angle at all times is quite high, thus it is likely that there is frames where this did occur. This is nevertheless a negligible source of error compared to other sources in 3D motion analysis.

Marker placement

Marker placement was conducted by the same personnel for every subject and the personnel had sufficient knowledge of the human anatomy and did go through specific training of the specific marker placement setup for this project. The markers on the wobble board were permanently placed on the board and had therefore the same position at all times. A study investigated the intra- and inter-examiner precision with which local positions of pelvis and lower limb palpable bony anatomical landmarks was identified. The intra- and inter-examiner precision (RMS distance from the mean position) resulted in the range of 6-21 mm and 13-25 mm, respectively (della, Cappozzo, & Kerrigan, 1999). This causes significant differences in joint angle estimation and is crucial to the precision of 3D motion. However, there were no joint angle estimations in our study and measures were taken to minimize the magnitude of the marker placement errors.

Soft tissue artefact

Soft tissue artefact (STA) is movement of the skin, or soft tissue in relation to the underlying bone and cause variances between actual skeletal movement, and movement recorded according to the markers attached to the skin. Soft tissue motion relative to the underlying bone has been measured up to twenty millimetres in task-dependent motions as for example gait (Fuller, Liu, Murphy, & Mann, 1997). The movement of the skin represents an artefact which affects the estimation of the skeletal system kinematics, and is regarded as the most critical source of error in human movement analysis, hence the results from tests using skin markers should be interpreted with caution (Leardini, Chiari, della, & Cappozzo, 2005). Alternatives such as bone pins can reduce skin movement, however it can lead to underestimations of STA (Stagni, Fantozzi, Cappello, & Leardini, 2005). Placement of bone pins require more training, they are more expensive and somewhat painful which could interfere with the subjects’ performance.

It is important to consider the potential error of STA when interpreting results in 3D motion analysis, however in this study the movements consisted of low impact forces and relatively slow movements. Therefore the STA would primarily be due to movement of the skin because of joint movements rather than from impact forces.

Missing markers

Circumstances can occur making reflective marker positions disappear from the data set. This could be due to limbs blocking the cameras recording area of a marker or damages and/or dirt on the marker. The markers were examined and replaced with a new one if a disadvantage was detected. However, some gaps in the data set did occur in our study and a gap-filling procedure was conducted to fill these gaps as described by Federolf (in press). New data points in the vector space get created by projecting the missing marker’s trace based on nearby functional markers. This procedure eliminate gaps in the dataset, however the new trajectory of the missing marker may differ from what would be its original trajectory, and could therefore be a source of error in the data analysis.

7. Conclusion

Hypothesis one was, that there would be a significant improvement in balance performance when standing on a wobble board with respect to number of attempts. This hypothesis was confirmed, and the results showed that there was largest learning effect the first 2-3 days.

Hypothesis two was, that the relative contribution of principal components quantifying the main types of body sway to the whole postural movements would decrease as subjects improve in balance performance, while the contribution of higher-order movement components increase. This hypothesis was not confirmed as there was no statistical significance in the change of the relative contribution of the principal movements throughout the tests.

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Abbreviations

BOS	Base of support
BS	Balance score
COG	Centre of gravity
COM	Centre of mass
COP	Centre of pressure
EV	Eigenvalue
GCS	Global coordinate system
PC	Principal component
PCA	Principal component analysis
PM	Principal movement
STA	Soft tissue artefact

Appendices

Appendix 1: *Information to subjects / Written consent*

Appendix 2: *Questionnaire for subjects*

Appendix 3: *Matlab script for calculating PCA, BS and missing markers.*

Appendix 4: *Abstract for ECSS 2013 in Barceolna [Accepted for 10 min oral presentation]*

Appendix 5: *Reply from REK*

Appendix 1: Information to subjects

Forespørsel om deltakelse i forskningsprosjekt

for personer som er aktive i idrett/mosjonsaktiviteter uten spesielt fokus på balansetrening

I forbindelse med masterprosjekt i biomekanikk vil Forskningssenter for trening og prestasjon ved Norges idrettshøgskole foreta noen målinger som kan gi informasjon om adaptasjon til balansetrening. I den sammenheng inviteres du til å delta i følgende forskningsprosjekt:

"Postural Movements and trunk muscle coordination when learning a balance task"

Bakgrunn og hensikt

Dette er et spørsmål til deg om å delta i en forskningsstudie som skal undersøke hvordan balansetrening over kort tid påvirker kroppsbeherskelse og balanseevne. Ved å sammenligne mellom før- og etter en treningsperiode kan vi få informasjon om hvordan balansetrening fungerer, og hvilke biomekaniske aspekter som forandres. Studien og testene som skal gjennomføres er godkjent av regional komité for medisinsk og helsefaglig forskning.

Hva innebærer studien?

Hvis du velger å delta i studien, vil du gjennomgå ulike tester på et tidspunkt som passer for deg. Testingen foregår i laboratoriene på Norges idrettshøgskole.

Deltagelse i prosjektet vil kreve opptil to uker av din tid. Hvor du må møte opp på laboratoriet ved Norges Idrettshøgskole fem (to?) ganger. Det vil da bli utført to hoved-tester og tre mindre tester. Testene som gjennomføres er lette balanseøvelser på balansebrett (wobble board), hvor biomekaniske målinger vil bli gjort. Disse målingene vil bestå av kinematikk, elektromyografi og kraftplattformmålinger. Du vil også bli stilt spørsmål om din treningsbakgrunn. Se vedlegg A for detaljer om testene.

Mulige fordeler og ulemper

Testene i prosjektet vil ikke forårsake noe ubehag, men noe stølhet kan forekomme. Dermed innebærer studien også svært få ulemper for deg.

Ved å delta i studien vil du få informasjon om dine balanseegenskaper og mulighet til å forbedre denne. Øvelsene er også gode for stabilisering av ankelleddet og dermed forhindring av skader. Når studien avsluttes, vil du kunne sammenligne dine egne målinger med gjennomsnittsverdiene fra alle deltagerne i prosjektet.

Hva skjer med informasjonen om deg?

Informasjonen som registreres om deg skal kun brukes slik som beskrevet i hensikten med studien. Alle opplysningene og testresultatene vil bli behandlet uten navn og fødselsnummer eller andre direkte gjenkjennende opplysninger. En talkode knytter deg til dine opplysninger og testresultater gjennom en navneliste.

Det er kun autorisert personell knyttet til prosjektet som har adgang til navnelisten og som kan finne tilbake til deg. Når resultatene fra prosjektet er ferdig behandlet og prosjektet er avsluttet, vil navnelisten bli slettet, slik at dine resultater ikke kan spores tilbake til deg. Prosjektet planlegges å avsluttes innen utgangen av 2013.

Det vil ikke være mulig å identifisere deg i resultatene av studien når disse publiseres.

Frivillig deltakelse
Det er frivillig å delta i studien. Du kan når som helst, og uten å oppgi noen grunn, trekke ditt samtykke til å delta i studien. Dette vil ikke få konsekvenser for deg. Dersom du ønsker å delta, undertegner du samtykkeerklæringen på siste side. Om du nå sier ja til å delta, kan du senere trekke tilbake ditt samtykke uten at det vil få konsekvenser for deg. Dersom du senere ønsker å trekke deg eller har spørsmål til studien, kan du kontakte Even Granerud, telefon +47 47 34 67 22 eller even.granerud@nih.no

Ytterligere informasjon om studien finnes i kapittel A – *utdypende forklaring av hva studien innebærer.*
Ytterligere informasjon om personvern og forsikring finnes i kapittel B – *Personvern, økonomi og forsikring.*

Samtykkeerklæring følger etter kapittel B.

Kapittel A- utdypende forklaring av hva studien innebærer

Kriterier for deltakelse

- Du må være mellom 18 og 35 år.
- Du må ikke ha drevet langvarig systematisk balansetrening.
- Dersom du har skader i kneet, i hoften, i hamstringsmuskulaturen eller quadricepsmuskulaturen, kan du ikke delta i studien.

Bakgrunnsinformasjon om studien

Balanse er en egenskap som er kritisk for mennesket. Likevel er menneskekroppen relativt dårlig tilpasset vertikal balanse; den har høyt tyngdepunkt, den består av mange bevegelige segmenter opp på hverandre og har liten understøtteflate. Fordelen med en slik multisegmental utforming er at balansen kan bevares i mange ulike stillinger og under bevegelser. Men dette stiller store krav til hjernens evne til informasjonsbehandling. På grunn av de biomekaniske forutsetningene, men også fordi livet stort sett leves i bevegelse, er balanse i vår sammenheng dynamisk, ikke statisk. Balansetrening benyttes i mange sammenhenger, både med helseperspektiv og innen toppidrett.

Det finnes et fåtall studier omhandlende kroppskontroll og forandring i holdning ved innlæring av nye balanseøvelser. Denne studien er et innledende forsøk på å samle inn mer informasjon om innlæring av balanse i tillegg til bruk av en analysemetode som er lite utbredt i biomekanikken.

Tidsskjema – hva skjer, og når skjer det?

Når du har lest gjennom denne informasjonen, vurderer du om du ønsker å delta i studien. Når du har tatt en avgjørelse, fyller du ut samtykkeerklæringen på siste side, og returnerer den til Even Granerud. Etter at du har gitt ditt samtykke, avtaler vi et tidspunkt for testing som passer for deg.

Du kan endre din avgjørelse om å delta/ikke delta når som helst. Du kan velge å avbryte testene underveis, hvis du ønsker det. Du vil ikke bli bedt om å oppgi nærmere forklaring eller årsak hvis du trekker deg.

Testingen gjennomføres til avtalt tid, i løpet av høsten 2012.

Undersøkelsene som blir gjort av deg

Du møter til testing uten å ha varmet opp på forhånd. Du må stille lettkledd (undertøy) for at utstyret som skal brukes skal være så presist som mulig. Testene gjennomføres uten sko.

Spørsmålene om din treningsbakgrunn vil inneholde:

- Fødselsdato
- Din kroppshøyde (kan måles på stedet)
- Hvilket år du begynte å være aktiv i idrett/mosjonsaktivitet

- Din nåværende ukentlige treningsmengde
- Eventuelle skader du har/har hatt

Det vil bli utført opptil fem tester over en to ukers periode, hvor pre- og post-testene er de mest omfattende. I tillegg må du trene balanse på balansebrett 3-5 ganger i uken. Dette treningsprogrammet vil du få innføring i og et eget skriv om.

Hovedtestene er som følger:

Hva	**Tid**	**Hvordan**
Antropometriske data	5 min	Kun første gang. Måling av høyde og vekt
Klargjøring (EMG)	30 min	Barbering og rensing av hud med isopropanol for optimal kontakt mellom hud og EMG-elektrode
Klargjøring (Kinematikk)	30 min	Plassering av refleksmarkører med dobbeltsidig tape, slik at disse kan bli oppdaget av infrarøde kameraer
Oppvarming	5-10 min	Sykling på ergometersykkel
Testing	2 min x 5 + pause	Det vil bli gjort opptak av alle målinger med 2 minutters intervaller. Forsøksperson vil da prøve å holde balansen på balansebrettet uten å komme i kontakt med underlaget i 2 minutter. Dette vil bli gjort 5 ganger med 2 minutters pause mellom hvert forsøk
Fjerning av utstyr	15 min	EMG-elektroder og refleksmarkører vil bli fjernet av testpersonell

Testing er ferdig

Mulige ubehag/ulemper

Testene i prosjektet vil ikke føre til ubehag. Noe stølhet kan forekomme etter første test. Den største ulempen ved å delta i studien, er at du må bruke opptil to timer av din tid per gang på laboratoriet.

Mulige fordeler

Ved å delta i studien, vil du få mulighet til å forbedre din balanse og stabilitet. Når studien avsluttes, vil du kunne sammenligne dine egne målinger med gjennomsnittsverdiene fra alle deltagerne i prosjektet. Du vil også få et innblikk i hvordan forskning på idrett foregår. Dette kan være interessant for deg som studerer eller vurderer å studere idrett.

Kapittel B - Personvern, økonomi og forsikring

Personvern
Opplysninger som registreres om deg er: Navn, alder, kroppshøyde, treningsbakgrunn, og resultater fra de beskrevne testene.

Informasjonen som registreres om deg skal kun brukes slik som beskrevet i hensikten med studien. Alle opplysningene og prøvene vil bli behandlet uten navn og fødselsnummer eller andre direkte gjenkjennende opplysninger. En tallkode knytter deg til dine opplysninger og testresultater gjennom en navneliste.

Det er kun autorisert personell knyttet til prosjektet som har adgang til navnelisten og som kan finne tilbake til deg. Når resultatene fra prosjektet er ferdig behandlet og prosjektet er avsluttet, vil navnelistene bli slettet, slik at dine resultater ikke kan spores tilbake til deg. Prosjektet planlegges å avsluttes innen utgangen av 2013.

Andre forskere ved Norges idrettshøgskole vil kunne be om tilgang til det anonyme materialet, til bruk i sammenligning med andre grupper idrettsutøvere eller personer.

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Rett til innsyn og sletting av opplysninger om deg
Hvis du sier ja til å delta i studien, har du rett til å få innsyn i hvilke opplysninger som er registrert om deg. Du har videre rett til å få korrigert eventuelle feil i de opplysningene vi har registrert. Dersom du trekker deg fra studien, kan du kreve å få slettet innsamlede opplysninger, med mindre opplysningene allerede er inngått i analyser eller brukt i vitenskapelige publikasjoner.

Økonomi og Norges idrettshøgskoles rolle
Studien er finansiert gjennom midler fra Norges idrettshøgskole og Forskningssenter for trening og prestasjon. Denne finansieringen innebærer ingen interessekonflikter, etiske eller praktiske utfordringer.

Forsikring
Staten er selvassurandør

Informasjon om utfallet av studien
Som deltager i prosjektet har du rett til å få opplyst både dine egne resultater, og informasjon om resultatene av studien totalt sett. Du kan få tilsendt informasjonen ved å kontakte even.granerud@nih.no.

Samtykke til deltakelse i studien

Jeg er villig til å delta i studien

(Signert av prosjektdeltaker, dato)

Jeg bekrefter å ha gitt informasjon om studien

(Signert, rolle i studien, dato)

Appendix 2: Questionnaire for subjects

Anthropometry and background information

Name/subject id:

Height (cm):

Weight (kg):

Age:

Training background (what – for how long?):

Balance training background:

____

____

____

Shoe size (eu) / foot length (cm):

____

Dominant hand / dominant leg:

____

Have you had/do you have any injuries related to (if so: when, for how long, how many times):

Ankle:____

Knee:____

Spine:____

Hip:____

Have you had/do you have any pain related to any of the following segments:

Ankle:____

Knee:____

Spine:____

Hip:____

Do you use glasses or lenses (if so wear them during testing):

____

Do you experience/have experienced any dizziness within the past 6 months:

____

Have you ever fainted (how many times? For which reason?):

____

Do you have any neurological disorders (for example epilepsy):

____

Do you have any allergies related to glue, bandages etc:

____

Do you smoke or use snus (quantify):

____

Appendix 3: Matlab script; read in data and BS.

```
%
%  PCA Workshop 2012
%
%  Peter Federolf
%
%  created: 2012-10-2
%  last modified:
%
%  content:
%   * read in data from tsv file (--> function "readtsv.m")
%   * organize data into standard vector
%   * determine gaps in the markerset. Remove whol marker if it has
%     gaps.
%   * prepare data for movie
%   * create a movie from original datapoints (--> function "movie.m")

%%
clear all;
close all;

%%  programming choices

create_movie = 0;   % 0: no movies (for fast computation)
                    % 1: display movie (for validation)

%%  read in data
Subjects = Subjects_files;


for subj = 1:11
    for day = 1:5
        for trl = 1:5
% creating filename and read in data
file_Path = Subjects(subj).TestingDay(day).trial(trl).file

%if file_Path ~= ''
[number_of_frames,number_of_cameras,number_of_markers,sample_frequency
,...
   signal,markernames] = readtsv_ext(file_Path);



%% reorganize data

% PF, 2012-10-3: Clusters not considered in this first step
marker_order_for_analysis = {...
    'RCA','LCA','RFM1','LFM1','RVMH','LVMH','RST','LST',... % Foot
%markers
    'RTAM','LTAM','RFAL','LFAL','RFLE','RFME','LFLE','LFME',...%Ankle,
%Knee
    'RFT','LFT','RIAS','LIAS','RIPS','LIPS',...  %Trochander and
%Pelvis
    'TV10','CV7','SXS','SJN',...  %spine and thorax
    'RAC','RSHO','RHLE','RHME','RRSP','RUSP',... %right shoulder & arm
    'LAC','LSHO','LHLE','LHME','LRSP','LUSP',... %left shoulder & arm
    'RAH','LAH','RLT','LLT','RPH','LPH','SAS'};   %head markers
```

```
n_marker_order_for_analysis = size(marker_order_for_analysis,2);


marker_wobbleboard = {...
    'WBA','WBRL','WBP','WBLL'};     %Removed ,'WBAR'

n_wobbleboard = size(marker_wobbleboard,2);



%%

% The following loop searches in "marker_wobbleboard" for the string
of
% each marker listed in "marker_order_for_analysis" and returns the
% position. Then it creates a new Datamatrix where the order of the
% coordinates aggrees with the order in "marker_order_for_analysis"

Data_WobbleBoard = zeros(number_of_frames,n_wobbleboard*3);
delete_markers = [];
for i = 1:n_wobbleboard
    for ii = 1:number_of_markers
        if ~isempty( findstr( cell2mat(markernames(ii)),...
                cell2mat(marker_order_for_analysis(i)) ) )
            mrk_index(i) = ii;
        end
    end
    Data_WobbleBoard(:, i*3-2:i*3) = signal( :, mrk_index(i)...
        *3-2:mrk_index(i)*3);

    % display warning in Command Window if a marker has gaps
    j = 1;
    while j<number_of_frames
        gap = 0;
        if  Data_WobbleBoard(j, i*3-2)==0 && Data_WobbleBoard...
                (j, i*3-1)==0 && Data_WobbleBoard(j, i*3)==0
            gap = 1;
            j = number_of_frames;
        else
            j=j+1;
        end
        if gap==1
            disp(['Warning!!  Marker ',marker_order_for_analysis(i)...
                ,' has gaps!!'] )
            delete_markers = [delete_markers, i]
        end
    end
end

%% Delete x and y coordinates of WB markers

    Data_WobbleBoard_xyz = Data_WobbleBoard;
    clear Data_WobbleBoard
    Data_WobbleBoard = Data_WobbleBoard_xyz(:, 3:3:12);
%end
%% cut off first 15 sec in which sbjects were adjusting +
```

```
% cut off last 15 sec

cut_off_time = 10;
cut_off_frames = cut_off_time*sample_frequency;

cut_off_time_end = 120;
cut_off_time_end_start = 115;

cut_off_frames_end = cut_off_time_end*sample_frequency;
cut_off_frames_end_start = cut_off_time_end_start*sample_frequency;

Data_WobbleBoard(cut_off_frames_end_start:cut_off_frames_end,:) = [];
Data_WobbleBoard(1:cut_off_frames,:) = [];

if create_movie
    movie(Data_WobbleBoard, 'Original_movement', create_movie, Subject
)
end

%% Calculate stdev of wobble board marker movement as Balance Score

mean_WobbleBoard_position = mean(Data_WobbleBoard,1);
std_WobbleBoard_position = std(Data_WobbleBoard,1,1);

BalanceScore(trl,day,subj) = sum(std_WobbleBoard_position);

        end %trl
    end %day
end %subj
```

Appendix 3: Matlab script; main program

```
%
%  Wobble board project 2012-2013
%
%  Peter Federolf, Even Granerud
%
%  created: 2013-5-20  Peter Federolf
%  last modified:
%
%  content:
%   * read in cleaned data
%   * normalize
%   * combine into one matrix
%   * PCA
%   * save results

%   Output:
%   *

clear all;
close all;

file_Path = 'E:\2013_WOBBLEBOARD\matlab\Results';

%initializations
all_Data_normalized =  zeros(11*5*5*43201 , 147);  % 11*5*5*43201

disp('initialization complete')

for subj = 1:11
    disp(['processing subject ',num2str(subj)])
    for day = 1:5
        for trl = 1:5

    File_name =
['Data_',num2str(subj),'_',num2str(day),'_',num2str(trl)];
    File_ = fullfile(file_Path, File_name);

    A = load(File_);
    Data = A.Data_Matrix;

    if (subj == 1) || (subj == 2)
        for coordin = [1:3: size(Data,2)-2]
        Data(:,coordin) = -Data(:,coordin);   %change x-coordinates
        Data(:,coordin+1) = -Data(:,coordin+1); %change y-coordinates
        end
    end


    %% Normalization
    mean_marker{subj,day,trl} = mean(Data);

    stdv_marker{subj,day,trl} = std(Data);

    Data_normalized = (Data - repmat(mean_marker{subj,day,trl},...
                                     size(Data,1),1)) ./ ...
```

```
                        repmat(stdv_marker{subj,day,trl},...
                                      size(Data,1),1) ;

    for i = 1: size(Data_normalized ,1)
        d_norm(i) = norm( Data_normalized (i,:) );
    end
    mean_d_norm{subj,day,trl} = mean(d_norm);

    Data_normalized = Data_normalized/mean_d_norm{subj,day,trl};

    %% build input for PCA
    lines = size(Data,1);
    pointer = ( ((subj-1)*25)+(((day-1)*5+1)+(trl-1)))*lines -43201 +
1;

    all_Data_normalized( pointer : pointer+43201-1 ,:) =
Data_normalized;



    %% save data and normalization
    Output_Name =  strcat('mean_d_norm_',num2str(subj),'_',...
        num2str(day),'_',num2str(trl),'.mat');
    Out_Path = fullfile('Results',Output_Name);
    save( Out_Path , 'mean_d_norm')

    Output_Name =  strcat('d_norm_',num2str(subj),'_',...
        num2str(day),'_',num2str(trl),'.mat');
    Out_Path = fullfile('Results',Output_Name);
    save( Out_Path , 'd_norm')

    Output_Name =  strcat('Stdv_marker_',num2str(subj),'_',...
        num2str(day),'_',num2str(trl),'.mat');
    Out_Path = fullfile('Results',Output_Name);
    save( Out_Path , 'stdv_marker')

    Output_Name =  strcat('Mean_markers_',num2str(subj),'_',...
        num2str(day),'_',num2str(trl),'.mat');
    Out_Path = fullfile('Results',Output_Name);
    save( Out_Path , 'mean_marker')

    Output_Name =  strcat('pointer_',num2str(subj),'_',...
        num2str(day),'_',num2str(trl),'.mat');
    Out_Path = fullfile('Results',Output_Name);
    save( Out_Path , 'pointer')

    Output_Name =  strcat('Data_normalized_',num2str(subj),'_',...
        num2str(day),'_',num2str(trl),'.mat');
    Out_Path = fullfile('Results',Output_Name);
    save( Out_Path , 'Data_normalized')

    clear mean_d_norm mean_marker stdv_marker Data_normalized d_norm



        end
    end
end
```

```
clear pointer lines Data_normalized i Data A File_* subj day trl
%% resample
samples = 240;
all_Data_resampled = all_Data_normalized...
    (1:samples:size(all_Data_normalized,1) , : );

clear all_Data_normalized

disp('now calculating PCA')
PCA_result = PCA( all_Data_resampled );




EV_Spectrum = PCA_result.Eigenvalues;
    Output_Name =  strcat('PCA_EVs.mat');
    Out_Path = fullfile('Results',Output_Name);
    save( Out_Path , 'EV_Spectrum')

PC_vectors = PCA_result.Eigenvectors;
    Output_Name =  strcat('PCA_Vectors.mat');
    Out_Path = fullfile('Results',Output_Name);
    save( Out_Path , 'PC_vectors')


disp('saving PC-scores')

counter=0;
for subj = 1:11
    disp(['processing PC-results for subject ',num2str(subj)])
    for day = 1:5
        for trl = 1:5


            File_name = ['Data_normalized_',num2str(subj),...
                '_',num2str(day),'_',num2str(trl)];
            File_ = fullfile(file_Path, File_name);
            B = load(File_);
            Data_normalized = B.Data_normalized;

            PC_scores = Data_normalized*PC_vectors;

            counter = counter+1;
            PC_relative_Variance(counter,:) = ...
                var(PC_scores)/sum(var(PC_scores))*100;

        end
    end
end
```

Appendix 3: Matlab script; predict missing markers

```
function [ ReconstructedFullDataSet ] = PredictMissingMarkers(...
    Data_gaps, nearNeighbours, secondaryNeighbours )
% PredictMissingMarkers
% searches for gaps in the marker coordinates and fills these gaps
assuming
% that correlations between variables in the full dataset will
% also exist in the dataset with gaps.
%
% Input:
% Data_gaps: matrix with marker data organized in the form
%            [ x1(t1), y1(t1), z1, x2, y2, z2, x3, ..., zn(t1)
%              x1(t2), y1(t2), ...
%               ...                                     ...
%              x1(tm), y1(tm), ...                    , zn(tm)]
% nearMeighbors: if it is known which markers have gaps, then
neighbouring
%                markers can be pointed out to improve the prediction
%                (see paper)
%
% Output:
% ReconstructedFullDataSet: Matrix in the same form as the input
matrix
%                           with colums that had gaps replaced by a
%                           reconstructed marker trajectory

% (c) Peter Federolf, 2013

%% Variable Definitions

columns = size(Data_gaps,2);
frames  = size(Data_gaps,1);

define_weights = ones(1,columns/3);

if nargin==1
elseif nargin==2 || nargin==3

    for i = 1:size(nearNeighbours,2)
    define_weights(nearNeighbours(i))= 10;
    end

elseif nargin==3

    for i = 1:size(secondaryNeighbours,2)
    define_weights(secondaryNeighbours(i))= 5;
    end

end




%% Step 1: Detect which columns have gaps and where
columns_with_gaps = [];
frames_with_gaps = [];
```

```
gaps_in_file = 0;
for j=1:columns
    if sum(isnan(Data_gaps(:,j) ))
        columns_with_gaps = [columns_with_gaps, j];
        frames_with_gaps(:,j) = isnan(Data_gaps(:,j));
        gaps_in_file = 1;
    end
end


if gaps_in_file

Matrix_Zeroed_compromisedColums = Data_gaps;
for j = flipdim(columns_with_gaps,2)   %note: large j to be deleted
first
    Matrix_Zeroed_compromisedColums(:,j) = zeros(size(Data_gaps,1),1);
end


%% Step 2: center the data by subtracting a mean trajectory,
%          then define the matices needed for the prediction


mean_trajectory.x = ...
    mean(Matrix_Zeroed_compromisedColums(:,(1:3:columns)),2);
mean_trajectory.y = ...
    mean(Matrix_Zeroed_compromisedColums(:,(2:3:columns)),2);
mean_trajectory.z = ...
    mean(Matrix_Zeroed_compromisedColums(:,(3:3:columns)),2);

Matrix_Zeroed_compromisedColums(:,1:3:columns) = ...
    Matrix_Zeroed_compromisedColums(:,1:3:columns)-...
        repmat(mean_trajectory.x,1,columns/3);
Matrix_Zeroed_compromisedColums(:,2:3:columns) = ...
    Matrix_Zeroed_compromisedColums(:,2:3:columns)-...
        repmat(mean_trajectory.y,1,columns/3);

Data_gaps(:,1:3:columns) = ...
    Data_gaps(:,1:3:columns)-...
        repmat(mean_trajectory.x,1,columns/3);
Data_gaps(:,2:3:columns) = ...
    Data_gaps(:,2:3:columns)-...
        repmat(mean_trajectory.y,1,columns/3);


% Matrix_Zeroed_compromisedColums is recalculated after removing the
mean
% trajectory:
Matrix_Zeroed_compromisedColums = Data_gaps;
for j = flipdim(columns_with_gaps,2)   %note: large j to be deleted
first
    Matrix_Zeroed_compromisedColums(:,j) = zeros(size(Data_gaps,1),1);
end


Matrix_with_all_Markers = Data_gaps;
```

```
Matrix_Reduced_Zeroed_compromisedColums =
Matrix_Zeroed_compromisedColums;
for i=frames:-1:1
    if sum(frames_with_gaps(i,:))
        Matrix_with_all_Markers(i,:) = [];
        Matrix_Reduced_Zeroed_compromisedColums(i,:) = [];
    end
end


%% Step 3: normalization: all markers are treated as if they carry the
same
%          amount of information: normalization to unit variance.
%          Then markers are multiplied with a weight vector that may
%          emphasise adjacent markers for higher precision.


mean_Matrix_Zeroed_compromisedColums =...
    mean(Matrix_Zeroed_compromisedColums,1);
mean_Matrix_with_all_Markers = mean(Matrix_with_all_Markers,1);
mean_ReducedMatrix = mean(Matrix_Reduced_Zeroed_compromisedColums,1);
difference_means =...
    mean_Matrix_with_all_Markers-mean_Matrix_Zeroed_compromisedColums;
stdev_Matrix_with_all_Markers = std(Matrix_with_all_Markers,1,1);


Matrix_Zeroed_compromisedColums = (Matrix_Zeroed_compromisedColums-...
    repmat(mean_ReducedMatrix,size...
    (Matrix_Zeroed_compromisedColums ,1),1))./...
    repmat(stdev_Matrix_with_all_Markers,size...
    (Matrix_Zeroed_compromisedColums ,1),1).*...
    repmat(reshape([1 1 1]'*define_weights,1,[]),...
    size(Matrix_Zeroed_compromisedColums ,1),1);
Matrix_with_all_Markers = (Matrix_with_all_Markers-...
    repmat(mean_Matrix_with_all_Markers,size...
    (Matrix_with_all_Markers ,1),1))./...
    repmat(stdev_Matrix_with_all_Markers,size...
    (Matrix_with_all_Markers ,1),1).*...
    repmat(reshape([1 1 1]'*define_weights,1,[]),...
    size(Matrix_with_all_Markers ,1),1);
Matrix_Reduced_Zeroed_compromisedColums = ...
    (Matrix_Reduced_Zeroed_compromisedColums - ...
    repmat(mean_ReducedMatrix,size...
    (Matrix_Reduced_Zeroed_compromisedColums ,1),1))./...
    repmat(stdev_Matrix_with_all_Markers,size...
    (Matrix_with_all_Markers ,1),1).*...
    repmat(reshape([1 1 1]'*define_weights,1,[]),...
    size(Matrix_with_all_Markers ,1),1);


%% Step 4: Perform a PCA on the incomplete and full Markersets
PCA_result_full = PCA_MMA(Matrix_with_all_Markers);
PC_vectors_full = PCA_result_full.Eigenvectors;

PCA_result_incomplete =
PCA_MMA(Matrix_Reduced_Zeroed_compromisedColums);
PC_vectors_incomplete = PCA_result_incomplete.Eigenvectors;
```

```
%% Step 5: Calculate Transformation Matrix for Principal Movements
%          Transform Data first into incomplete-, then into full-PC
basis system.

CoordinateTransf = PC_vectors_full' * PC_vectors_incomplete;

Data_in_incomplete_PCCoordinates = ...
    (Matrix_Zeroed_compromisedColums*PC_vectors_incomplete);

Data_in_full_PCCoordinates =  ...
    Data_in_incomplete_PCCoordinates * CoordinateTransf;


%% Step 6: transform back into Marker coordinates, thereby
%reconstructing the missing marker

%initialization:
ReconstructedData = repmat(mean_Matrix_with_all_Markers,frames,1);

for k = 1: size(PC_vectors_full,1)-3
% NOTE: to reduce noise it may be beneficial to reduce the number of
% PC vectors considered in the reconstruction
    ReconstructedData = ReconstructedData +...

(Data_in_full_PCCoordinates(:,k)*PC_vectors_full(:,k)').*...
        repmat(stdev_Matrix_with_all_Markers,size...
        (ReconstructedData ,1),1)./...
        repmat(reshape([1 1 1]'*define_weights,1,[]),size...
        (Matrix_Zeroed_compromisedColums ,1),1);
end


%% Step 7: Add mean trajectory subtracted in step 2 to obtain original
%          dataset + missing marker

ReconstructedData(:,1:3:columns) = ...
    ReconstructedData(:,1:3:columns) + ...
    repmat(mean_trajectory.x,1,columns/3);

ReconstructedData(:,2:3:columns) = ...
    ReconstructedData(:,2:3:columns) + ...
    repmat(mean_trajectory.y,1,columns/3);


%% Prepare Output
ReconstructedFullDataSet = Data_gaps;
for j = columns_with_gaps
    ReconstructedFullDataSet(:,j) = ReconstructedData(:,j);
end

else
ReconstructedFullDataSet = Data_gaps;
end
end
```

Appendix 3: Matlab script; PCA

```
function PCA_result = PCA( InputData )
%UNTITLED5 Summary of this function goes here
%   Detailed explanation goes here

subtract_mean = 0;
% note: subtraction of the mean requires a
% lot of memory resources. Avoid if possible.

normalize_EV = 1;
n_eig = size(InputData,2)-3;    % how many EV should be calculated?
n_scores = size(InputData,2)-3; % how many PC-scores should be
calculated?

%%step 1: subtract mean
if subtract_mean
    mean_DataMatrix = mean(InputData,1);
    Data            = InputData - repmat(mean_DataMatrix,size...
        (InputData ,1),1);
else
    Data            = InputData;
end

%% step 2: compute covariance matrix on time series
c = cov(Data);

%
if normalize_EV
c = c/trace(c);  % normalize to trace 1 (sum of eigenvalues = 1 =
100%)
end

%% step 3: Eigenvalue decomposition
% determine eigenvalues, and corresponding eigenvectors
[v,lambda] = eigs(c,n_eig);
v = v(:,1:n_eig);



%% step 4: Calculate PC-Scores for the vectors in Data
% project walking pattern on space spanned by the eigenvectors
d_bar = Data*v;


%% Done:  build the output structure
PCA_result = [];
if subtract_mean
    PCA_result.mean_DataMatrix = mean_DataMatrix;
end
PCA_result.Eigenvectors = v;
PCA_result.Eigenvalues = diag(lambda);
PCA_result.scores = d_bar(:,1:n_scores);
end
```

Appendix 4: Abstract for ECSS Barcelona 2013

CHANGES IN POSTURE AND BALANCE PERFORMANCE DURING FIVE DAYS OF WOBBLE BOARD TRANING

Granerud, E. & Federolf, P.
Norwegian School of Sport Sciences, Oslo, Norway

Introduction

Human postural control is facilitated through postural movements such as ankle-, hip-, or multi-joint strategies (Winter, 1995). Principal component analysis (PCA) applied to kinematic marker offers a novel approach study the structure of postural movements by identifying and quantifying correlated segment motion (Federolf et al. 2012, in press). This study investigated if the structure of the postural movements changes as subjects learn to master a balance task (standing on a wobble board). It was hypothesized that the relative contribution of principal components quantifying the main types of body sway (e.g. ankle strategy) to the whole postural movements would decrease as subjects improved in performance, while the contribution of higher-order movement components might increase.

Methods

Eleven healthy male volunteers (age 25.1±1.7, weight 77.2±5.8 kg, height 1.80m±0.07) conducted a total of 25 120-second quiet stance trials on a wobble board, 5 trials per day during 5 consecutive days. The subjects' postural movements were recorded with a standard 3D-camera system (ProReflex, Qualisys INC., Gothenburg, Sweden) using 49 reflective markers distributed over all major body segments. For each timeframe, a 147-dimensional posture vector was defined that included all marker coordinates. The posture vectors of all trials of a subject were normalized and assembled into an input matrix for the PCA. The structure of a subject's postural movements were then characterized by calculating the relative contribution (RC) of the first 10 principal movement components (PCs) to the entire postural variation in one trial. For each trial, a "balance score" was calculated by totalling the standard deviation of the vertical position of 4 markers placed on the wobble board. A repeated measures ANOVA (Sidak correction) was conducted to determine differences in RC or balance score between trials.

Results

Balance performance on the wobble board improved over the first 2-3 test days with the balance score decreasing from 52.1±11.0 in the first trial to levels below 34.2±6.1 in all trials of the 4th and 5th day (mean±stdev). This change was significant ($F(1,24)=11.17$, $p<0.007$). However, no changes were observed in the structure of the postural movements as quantified by the first 10 PCs: $F(1,24)<1.42$, $p>0.98$ in the RC calculated for the first 10 PCs.

Discussion

The hypothesis was not confirmed. The results of this study suggest that the improvement in performing the wobble-board balance task was not related to changes in the structure or organization of postural movements as quantified by PCA-RC.

References

Federolf P, Roos L, Nigg B (2012). Footwear Science, 4:2, 115-122.
Federolf P, Reid R, Gilgien M, Haugen P, Smith G (in press) Scan J Med Sci Spor.
Winter DA (1995) Gait Posture, 3, 193-214.

Appendix 5: Reply from REK

14.06.2012 REK sør-øst

Forskningsprosjekt
Tilpasning av postural kontroll og muskelkoordinering ved innlæring av balanseøvelser

Vurdering:

I den vitenskaplige protokollens første avsnitt beskrives studien slik: Tjue unge friske studenter vil inkluderes i et to ukers balansetreningsprogram, med formål om å forbedre balansen, spesifikt på balansebrett.

Komiteen viser i den forbindelse til helseforskningslovens § 4 første ledd, hvor medisinsk og helsefaglig forskning forstås som virksomhet som utføres med vitenskaplig metodikk for å skaffe til veie ny kunnskap om helse og sykdom.

Komiteen mener formålet med denne studien ikke er å fremskaffe ny kunnskap om helse eller sykdom, men snarere å søke kunnskap som kan være med å forbedre trenings- og idrettsprestasjoner blant friske personer.

Prosjektet faller derfor utenfor komiteens mandat, jf. helseforskningslovens § 2.

Vedtak:

Prosjektet er ikke fremleggelsespliktig, jf. helseforskningslovens § 10, jf. helseforskningslovens § 4 annet ledd.

REK antar for øvrig at prosjektet kommer inn under de interne regler som gjelder ved forskningsansvarlig virksomhet. Søker bør derfor ta kontakt med enten forskerstøtteavdeling eller personvernombud for å avklare hvilke retningslinjer som er gjeldende.

Komiteens avgjørelse var enstemmig.

Forskningsprosjekt

Tilpasning av postural kontroll og muskelkoordinering ved innlæring av balanseøvelser

Vitenskapelig tittel:

Postural movements and trunk muscle coordination when learning a balance task

Prosjektbeskrivelse:
Prosjektet sammenligner biomekaniske data vedrørende balanse på balansebrett. Formålet er å kunne få ny informasjon om utvikling av postural kontroll og muskelkoordinering ved læring av nye balanseøvelser.
(Prosjektleders prosjektbeskrivelse)

Ref. nr.: 2012/939 Prosjektstart: 22.08.2012 Prosjektslutt: 22.08.2015

Behandlingsstatus: Utenfor mandatet
Prosjektleder: Jens Bojsen-Møller

Forskningsansvarlig(e): Norges Idrettshøgskole
Initiativtaker: Bidragsforskning
Finansieringskilder:

Norges Idrettshøgskole

Forskningsdata: Registerdata
Utvalg: Allmennbefolkning
Forskningsmetode:: Statistiske (kvantitative) analysemetoder
Antall forskningsdeltakere (Norge): 20

Behandlet i REK

Dato	REK
14.06.2012	REK sør-øst

Tilbake til oversikten

Kontakt REK

- Generelle spørsmål skal rettast til REK i din geografiske region
- Spørsmål om saker som er sende inn, skal rettast til den REK som har saka
- Du må skrive namn på aktuell REK (REK sør-øst, REK vest, REK midt eller REK nord) i emnefeltet på e-post til post@helseforskning.etikkom.no
- Komitésekretariata kan også kontaktast på telefon, e-post eller kontoradresse, som du finn under menyvalet Komiteer og møter

Ofte stilte spørsmål