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Changes in multi-segmented body movements and EMG activity while standing on firm and foam support surfaces

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Running title:

Movement pattern alterations to support surface conditions.

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Abstract

Postural control ensures stability during both static posture and locomotion by initiating corrective adjustments in body movement. This is particularly important when the conditions of the support surface change. We investigated the effects of standing on a compliant foam surface using twelve normal subjects (mean age 26 years) in terms of: linear movements at the head, shoulder, hip and knee; EMG activity of the tibialis anterior and gastrocnemius muscles and torques towards the support surface. As subjects repeated the trials with eyes open or closed, we were also able to determine the effects of vision on multi-segmented body movements during standing upon different support surface conditions.

As expected, EMG activity, torque variance values and body movements at all measured positions increased significantly when standing on foam compared with the firm surface. Linear knee and hip movements increased more, relative to shoulder and head movements while standing on foam. Vision stabilized the head and shoulder movements more than hip and knee movements while standing on foam support surface. Moreover, vision significantly reduced the tibialis anterior EMG activity and torque variance during the trials involving foam.

In conclusion, the foam support surface increased corrective muscle and torque activity, and changed the firm-surface multi-segmented body movement pattern. Vision improved the ability of postural control to handle compliant surface conditions. Several essential features of postural control have been found from recording movement from multiple points on the body, synchronized with recording torque and EMG.

Key Words: Human standing; EMG; Posturography; Vision; Firm; Foam.

1 Introduction

Assessments of quiet stance on a firm surface are not always sufficiently discriminative to distinguish healthy subjects from patients with various balance disorders (Johansson and Magnusson 1991). A number of balance-perturbing tests have therefore been developed to challenge the postural control system so as to reveal possible balance deficits. One of the simplest ways to impose more demand on the postural control system is to have the patient stand on a compliant foam surface which is believed to affect the accuracy of somatosensory information from cutaneous mechanoreceptors on the soles of the feet (Wu and Chiang 1997). The cutaneous mechanoreceptors on the soles of the feet serve to maintain postural stability by detecting displacement, velocity and acceleration of indentation of the skin as well as transient forces (Johansson and Vallbo 1980; Vedel and Roll 1982). The importance of mechanoreceptive information for postural control has been confirmed in several previous investigations (Kavounoudias et al. 1998; Stal et al. 2003). The destabilizing effects of standing on a foam surface have also been investigated previously in several studies (Blackburn et al. 2003; Jeka et al. 2004; Vrancken et al. 2005). However, there are few kinematical studies of how this destabilizing effect is expressed at key points of articulation between the major body segments (Gill et al. 2001; Allum et al. 2002; Blackburn et al. 2003; Riemann et al. 2003). Several of these studies have only investigated the trunk movements, disregarding the movements in the other body segments. To the best of our knowledge, no previous studies have been reported where the linear head, shoulder, hip, knee movements, torque activity towards the support surface and EMG activity in tibialis anterior and gastrocnemius muscles have been assessed simultaneously during firm and foam support surface conditions.

Human postural control is an incessant process since our upright stance and body structure are inherently, biomechanically unstable. The control of postural stability can be described in terms of a homeostatic system that requires sensory input, an integration centre and effectors that counteract the destabilization. Afferent information is obtained from visual, vestibular and somatosensory receptor systems and processed by the central nervous system to determine the current position and movement of the body, thereby allowing precise postural control responses (Nashner 1976; Riemann et al. 2003). The human body can be described biomechanically as made up of articulating body segments, where the ability to generate corrective motions of each segment is determined by limitations of the movements imposed by muscles, joints and tendons (Carlsöö 1961; Johansson and Magnusson 1991; Williams 1995). Postural muscles are located at numerous sites in the human body and include a number of muscles in the lower extremities such as the tibialis anterior, soleus and gastrocnemius muscles. These muscles play important roles in postural control as they oppose the destabilizing effects of gravity (Loram et al. 2004).

This study investigated the relative changes in movement at various articulation landmarks along the body, changes in torques induced towards the support surface and changes in EMG activity of the tibialis anterior and gastrocnemius, in subjects challenged by standing on a foam surface with eyes open or closed. The findings indicate that a number of postural strategies are employed to maintain stability that involves differential contributions by various body segments.

2 Methods and Materials

2.1 Subjects

Twelve healthy consenting volunteers (five males and seven female; mean age 26 years, range 18-37 years; mean height 1.74 m, range 1.66-1.83m; mean weight 70 kg, range 58-95 kg) performed a series of posturographic tests on a firm and foam surface. Subjects had no balance or musculoskeletal deficits, were not taking medication and refrained from alcohol 24 hours prior to testing. Experiments were performed in accordance to the Helsinki declaration of 1975.

2.2 Equipment

A force platform, recorded forces actuated at the feet with six degrees of freedom and an accuracy of 0.5 N. Data were sampled at 50 Hz.

An ultrasonic 3D-Motion Analysis system (Zebris™ CMS-HS Measuring System) measured movement of markers placed at five anatomical landmarks: Head (os zygomaticum), Shoulder (tuberculum majus), Hip (crista iliaca), Knee (lateral epicondyle of femur), and Ankle (lateral distal fibula head), see figure 1. The Zebris system tracked the position of each of the five markers in three dimensions, i.e., its anteroposterior, lateral and vertical position with an accuracy of 0.4 mm. The same Zebris™ system simultaneously recorded the EMG activity in the tibialis anterior and gastrocnemius muscle in both legs using surface electrodes. A computer simultaneously sampled the marker position data at 50 Hz and EMG activity in the muscles at 1500 Hz.

The recorded data from the force platform and 3D-Motion Analysis and EMG measurement systems were synchronized in time by off-line time matching of the reference signal, which was simultaneously sampled by both measurement systems.

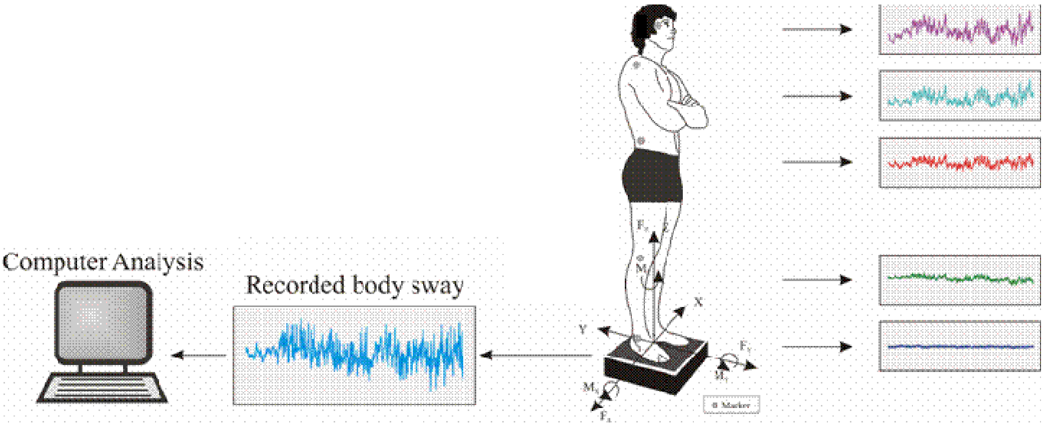


Figure 1. Schematic of the measurement system and position of the five Zebris markers attached on a subject standing on a force platform. The marker locations are shown as small circles.

2.3 Procedure

Four randomized tests, each lasting 120s, were performed:

- Standing on a firm surface with eyes open (Firm-EO) and eyes closed (Firm-EC)
- Standing on a foam surface with eyes open (Foam-EO) and eyes closed (Foam-EC)

Five Zebris™ markers were attached on the subject's right side which was turned towards the Zebris motion detector and EMG surface electrodes were placed over the tibialis anterior and gastrocnemius muscles of both legs. Subjects were instructed to stand upright and relaxed with arms crossed over the chest, feet at an angle of approximately 30 degrees open to the front with heels about 3 cm apart. In some tests, a block of foam was placed upon the platform and subjects were instructed to position their feet while standing on the foam in the same manner as explained above. The foam block was 40cm long, 36.5cm wide and 10cm in height, with a density of 32.6 kg/m^3. The subjects focused on a target at eye level at a distance of 1.5 m, or closed their eyes when instructed. Subjects listened to music through headphones to reduce any distractions.

2.4 Data analysis

Stability while standing is commonly analyzed using force platforms and the movements of the center of pressure (CoP), i.e., the point of application of the ground reaction force. We analyzed the torque values, where CoP = torque/(m*g); m=the assessed subjects weight and g= gravitational constant 9.81. Therefore changes in recorded torque, forwards and backwards, are equivalent to changes in CoP.

The linear anteroposterior body movements were expressed in terms of movement variance at the head, shoulders, hip and knee divided into three spectral categories i.e. all recorded movements (denoted Total); movements below 0.1Hz (<0.1 Hz) and movements above 0.1 Hz (>0.1 Hz). This allowed us to distinguish between smooth corrective changes of posture (i.e.<0.1 Hz) and fast corrective movements to maintain balance (i.e. >0.1 Hz) (Kristinsdottir et al. 2001). The frequency cut-off level of 0.1 Hz was based upon previous studies showing that vision effectively reduces the torque activity above 0.1 Hz towards the support surface when standing on a firm surface (Kristinsdottir et al. 2001; Stal et al. 2003). The anteroposterior torque values derived from force platform recordings were also divided into the same three spectral categories before the variance values for each spectral category were calculated. Before statistical analysis, the values of the linear movement variance were normalized using the subject's squared height before the statistical analysis thus providing inter-individual compensation for individual variation in height (Fransson 2005). Likewise, the torque variance values were normalized using the subject's squared height and squared weight, compensating for individual variation in height and weight. The squared nature of the variance algorithm requires normalization with squared parameters to achieve unit agreement. In each subject, the RMS EMG activity in the tibialis anterior and gastrocnemius muscles was normalized to that assessed, while standing with eyes open on firm surface.

Furthermore, quotients describing the ratio between the movement amplitude when the support surface were changed from firm to foam as well as when the eyes were open or closed, were calculated for each Zebris marker position. The statistical evaluation of the quotients show whether the movements of individual body segments where equality prone to change because of changes in test conditions.

The recorded EMG data from the tibialis anterior and gastrocnemius muscles of both legs during the entire test were band-pass filtered (20-200Hz), and a root mean square (RMS) value for the filtered EMG data was calculated. For each muscle, the average RMS EMG activity in both legs was thereafter calculated.

A fifth-order digital Finite duration Impulse Response (FIR) filter (Proakis and Manolakis 1989), with filter components selected to avoid aliasing, was used for spectral separation.

For each trail, all results were based on analysis of the entire 120 second test period.

2.5 Statistical analysis

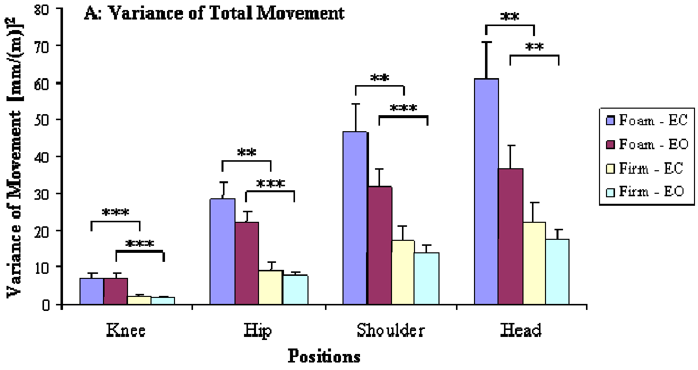
For each of the three spectral categories, statistical analysis was performed on the variance of the anteroposterior linear head, shoulders, hip and knee movements, recorded by the Zebris system, as well as on the variance of the anteroposterior torque recorded by the force platform.

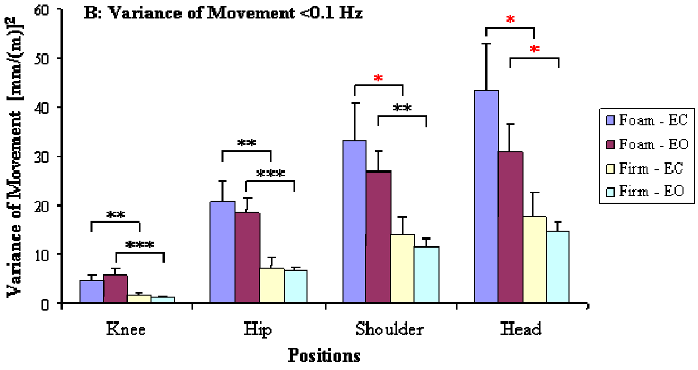
The Wilcoxon matched-pairs signed-rank test (Exact sig. 2-tailed) (Altman 1991) was used to statistically compare results between the test conditions and used in the evaluation of the quotients describing the proportional differences between the body movements during the assessed trial conditions. In addition, a GLM Multivariate ANOVA (General Linear Model multivariate Analysis of Variance) statistical test on log-transformed values (Altman 1991) was used to determine whether vision or the type of support surface significantly affected results and whether there was a combined effect from vision and the type of support surface on measured linear body movement, torque activity and EMG activity. The GLM model accuracy was evaluated by testing the model residual for normal distribution.

Normality of value distribution was tested with the Shapiro-Wilk test. Non-parametric statistics were used in the statistical evaluation since all obtained analysis values were not normally distributed and normal distribution could not be attained by logarithmic transformation. The statistical analysis was carried out with Bonferroni correction for multiple comparisons and in the analysis, p-values < 0.01 was considered statistical significant (Altman 1991). However, we present the p-values < 0.05 in the figures (in red) and tables for consistency.

3 Results

3.1 Linear body movements





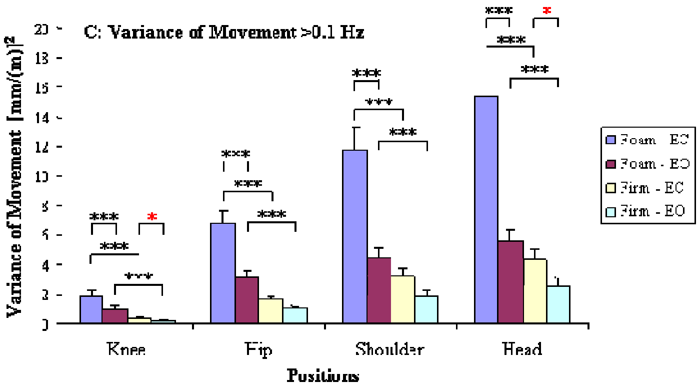


Figure 2. Variance values for linear head, shoulder, hip and knee movements in anteroposterior direction (mean and standard error of mean (SEM)) for A: Total body movement, B: Body movement <0.1 Hz, C: Body movement >0.1 Hz. The presented values have been normalized to the subject's height [mm/(m)]^2. The statistical differences found between firm and foam surface results while standing with eyes closed and eyes open, and between eyes closed and eyes open results while standing on the foam and firm surfaces are marked with asterisks, where *= p<0.05, ** = p<0.01 and *** = p<0.001.

Figure 2 shows that the foam surface significantly increased the amplitude of AP oscillations in all segments and in all spectral categories, i.e. total, body movements <0.1 Hz and body movements >0.1 Hz. With either eyes open or closed, the total movement variance was clearly larger while standing on a foam surface than when standing on a firm surface (p<0.01). The proportional movement differences for each body position are presented in table 2. Interestingly, the foam support increased the movements of the lower body segments more than the movements of the higher body segments, both with eyes closed (knee p<0.001; hip, shoulder and head, p<0.01), and with eyes open (knee, hip, shoulder p<0.001; head p<0.01). For details, see first section of table 2 - foam/firm quotients for EC and EO.

The variance of body movements below 0.1 Hz in the various conditions varied in the same way as the total variance. Again, the foam support surface increased the movements of the lower body segments to a larger extent than the movements of the higher body segments, while standing with eyes closed (knee, hip p<0.01; shoulder, head p<0.05) or open (knee, hip p<0.001; shoulder p<0.01; head p<0.05)(second section of table 2 - foam/firm quotients).

Also the variance of body movements above 0.1 Hz was clearly larger on foam than on the firm surfaces in all body segments, with both eyes closed and eyes open ($p<0.001$) (third section of table 2 - foam/firm quotients).

3.1.1 Visual influence on linear head, shoulder, hip and knee movements

Visual information only significantly influenced the body movements above 0.1 Hz (figure 2). Vision clearly reduced the knee, hip, shoulder and head movements above 0.1 Hz while standing on the foam surface ($p<0.001$). Vision also reduced the knee and head movements above 0.1 Hz while standing on the firm surface but these changes could only be determined at statistical level $p<0.05$.

3.1.2 GLM Multivariate ANOVA of body movements

Body movement variance		p-value		
Spectral category	Position	Vision	Support surface	Vision × Support surface
Total	Head	ns	<0.001	ns
	Shoulder	ns	<0.001	ns
	Hip	ns	<0.001	ns
	Knee	ns	<0.001	ns
<0.1 Hz	Head	ns	=0.001	ns
	Shoulder	ns	=0.001	ns
	Hip	ns	<0.001	ns
	Knee	ns	<0.001	ns
>0.1 Hz	Head	<0.001	<0.001	ns
	Shoulder	<0.001	<0.001	ns
	Hip	<0.001	<0.001	ns
	Knee	=0.001	<0.001	ns

Table 1. Statistical comparison of the body movement values using the GLM multivariate ANOVA method. The “ns” denotes no significant difference between the compared data groups.

The GLM analysis confirms that the type of support surface, i.e., firm or foam, significantly affected body movement at all measured positions in all spectral categories ($p=0.001$), see table 1. Recorded body movements at all measured sites were significantly larger while standing on the foam surface compared with the firm surface. Also, the GLM analysis shows that vision only had a significant effect in reducing body movements above 0.1 Hz (p=0.001) at all measured positions. It is also noteworthy that the statistical analysis did not show a combined effect of vision and support surface condition.

3.1.3 Proportional body movements

Movement quotients			Knee	Hip	Shoulder	Head
Spectral category	Test condition	Quotients				
Total	EC	Foam/Firm	4.59 (0.98)	5.53 (1.23)	3.81 (0.88)	3.93 (0.77)
	EO	Foam/Firm	5.59 (1.43)	3.50 (0.86)	2.64 (0.40)	2.41 (0.47)
	Firm	EC/EO	1.33 (0.21)	1.09 (0.24)	1.41 (0.29)	1.31 (0.28)
	Foam	EC/EO	1.15 (0.23)	1.57 (0.42)	1.88 (0.57)	2.40 (0.81)
<0.1 Hz	EC	Foam/Firm	4.29 (1.17)	5.97 (1.46)	3.98 (1.20)	4.39 (1.10)
	EO	Foam/Firm	6.26 (2.05)	3.78 (1.13)	2.86 (0.52)	2.71 (0.72)
	Firm	EC/EO	1.32 (0.26)	1.01 (0.27)	1.43 (0.34)	1.28 (0.33)
	Foam	EC/EO	0.98 (0.24)	1.45 (0.48)	1.82 (0.72)	2.73 (1.21)
>0.1 Hz	EC	Foam/Firm	6.28 (0.69)	4.92 (0.59)	4.11 (0.43)	3.87 (0.38)
	EO	Foam/Firm	5.05 (0.77)	3.33 (0.39)	2.62 (0.28)	2.44 (0.25)
	Firm	EC/EO	1.67 (0.17)	1.80 (0.29)	1.95 (0.30)	1.95 (0.28)
	Foam	EC/EO	2.12 (0.19)	2.37 (0.27)	2.79 (0.29)	2.89 (0.28)

Table 2. Summary of quotients (mean and (SEM)) comparing the average body movement values during different trials conditions.

Table 2 shows the EC/EO quotient values for the different body movements in the various test conditions, relative to the quotient values in the firm surface trials (the normal movement condition). The quotients show that vision reduced the body movements similarly at all body positions while standing on the **firm** surface. In the **foam** surface trials instead the head movements were significantly more reduced by vision than the total knee movements (p<0.01). Additionally, the knee and hip movements above 0.1 Hz were reduced significantly less by vision than the shoulder and head movements (p<0.01). Hence, access to visual information while standing on a foam support stabilized the head and shoulder in space more effectively than the other body parts.

The **foam/firm-quotients** for both the trials with **eyes closed** and **eyes open** conditions show that the knee and hip movements were more affected by the support surface than the shoulder and head movements. In particular, with eyes closed, the knee movements above 0.1 Hz were changed proportionally more than the shoulder and head movements when passing from a firm to a foam surface (p<0.01). Similarly, the hip movements above 0.1 Hz were changed proportionally more than the head movements (p<0.01).

When passing from a firm to a foam surface with eyes open, the total knee movements and the knee movements above 0.1 Hz were changed proportionally more than the shoulder and head movements (p<0.01). In turn, the hip movements above 0.1 Hz were changed proportionally more than the shoulder and head movements (p<0.01).

3.3 Force platform recordings

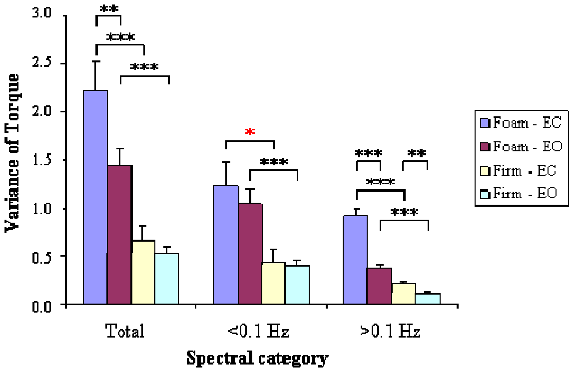


Figure 3. Anteroposterior torque variance values during the trials (mean and (SEM)) for variance of total torque, variance of torque <0.1Hz and variance of torque >0.1Hz. The variance values have been normalized with the subject's weight and height $[Nm/(Kg \cdot m)]^2$ and multiplied by 1000. The statistical differences found between firm and foam surface results while standing with eyes closed and eyes open, and between eyes closed and eyes open results while standing on foam and firm surfaces are marked with asterisks.

Figure 3 shows that the largest anteroposterior torque variations were obtained while the subjects stood on foam. The foam surface significantly increased the torque in all three spectral categories (total torque, torque <0.1 Hz and >0.1 Hz. The total torque variance was larger while standing on foam than on a firm support both with eyes open and eyes closed ($p<0.001$). However, when passing from a firm to a foam surface, the total torque variance increased by 177% with eyes open and by 234% with eyes closed.

The variance of torque below 0.1 Hz largely reflected the trend of the total variance. However, the differences between the foam and firm support was less pronounced while standing with eyes closed (increase by 165%, $p<0.05$) than while standing with eyes open (increase by 178%, $p<0.001$).

Similar to the body movements, the variance of torque above 0.1 Hz was larger when standing on foam than on the firm support, both with eyes closed and eyes open ($p<0.001$). Increase was 338% with eyes closed and 230% with eyes open).

3.3.1 Visual influence on torque values

Vision had a significant influence on both the variance of total torque and variance of torque above 0.1 Hz. Vision reduced the variance of total torque while standing on foam by 35 % ($p<0.01$), see figure 4. Vision reduced the variance of torque above 0.1 Hz as well, by 60 % ($p<0.001$) on the foam support and by 47 % ($p<0.01$) on the firm surface.

3.3.2 GLM Multivariate ANOVA analysis of torque values

Torque variance	p-value		
Spectral category	Vision	Support surface	Vision × Support surface
Total	ns	<0.001	ns
<0.1 Hz	ns	<0.001	ns
>0.1 Hz	<0.001	<0.001	ns

Table 3. Statistical comparison of the torque variance values using the GLM multivariate ANOVA method.

The GLM statistical test confirms that the support surface had a significant effect on the torque variance within all spectral categories (p<0.001), see table 3. The torque variance was significantly larger while standing on foam than on a firm support. Moreover, vision had a significant influence in reducing the torque values above 0.1 Hz (p<0.001). Finally, statistical evaluation did not show a significant interaction of vision and the support surface.

3.4 EMG activity

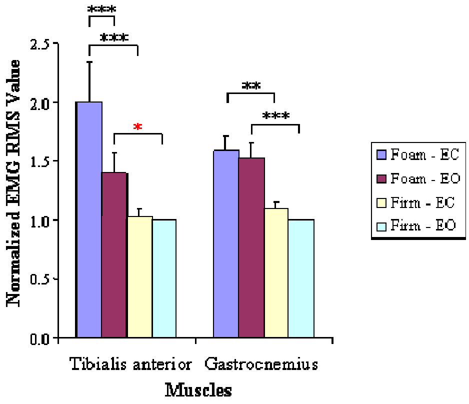


Figure 4. Normalized EMG RMS results recorded from the tibialis anterior and gastrocnemius muscles from standing on a firm surface or a foam surface (mean and (SEM)). The statistical differences found between the firm and the foam surface results while standing with eyes closed and eyes open, and between eyes closed and eyes open results while standing on foam and the firm surface are marked with asterisks. Note that the EMG activity during the trial while standing with eyes open on the firm surface serves as reference value.

Figure 4 shows that the gastrocnemius EMG activity increased when passing from a firm to a foam support. The increase was 45% when eyes were closed (p<0.01) and 52% when eyes were open (p<0.001).

The EMG activity in the tibialis anterior also increased by 94% when eyes were closed (p<0.001), while no significant change was observed when eyes were open.

3.4.1 Visual influence on EMG activation

Vision had no significant influence on the gastrocnemius EMG activity while standing on the foam surface or while standing on the firm surface. Instead, vision reduced the tibialis anterior EMG activity by 30 % while standing on foam (p<0.001).

3.4.2 GLM Multivariate ANOVA analysis of EMG activity

Body movement variance	p-value		
Muscle	Vision	Support surface	Vision × Support surface
Tibialis anterior [#]	ns	=0.002	ns
Gastrocnemius	ns	<0.001	ns

Table 4. Statistical comparison of the EMG activity values using the GLM multivariate ANOVA method. [#]The GLM model residual was not normally distributed. These statistical values may therefore be somewhat less accurate.

The EMG activity both in the gastrocnemius and tibialis anterior muscles was significantly larger while standing on foam than while standing on the firm surface (p=0.002), see table 4. However, no significant effect of vision or combined effects of vision and support surface condition were detected by the statistical analysis.

4 Discussion

The destabilizing effect of standing on a compliant surface, such as foam, is well known. However, using simultaneous recording of movement from multiple articulation points, force platform recordings and EMG activity, we can get a better understanding of the strategies employed by the body to maintain postural stability.

4.1 Effect of foam support surface on body movements and torque activity

The compliant foam support surface substantially increased the requirements of muscle activity, torques and changed the evoked body movement pattern at all measured sites. These responses were more prominent with eyes closed, as evidenced by the significant increase of fast body movements and torques above 0.1 Hz. Movements and torques below 0.1 Hz were to a lesser extent, increased by the foam than the high frequency movements and high frequency torques. Another finding was that the complaint foam support surface increased the movements of the lower body segments, e.g., the knee and hip movements proportionally more than shoulder and head movements, see table 2. These observations are in line with several previous reports showing that changed sensory information from vision and proprioception can have a major effect on postural control and the multi-segmented body movements (Kavounoudias et al. 1999; Perry et al. 2000; Kavounoudias et al. 2001; Blackburn et al. 2003; Vuillerme et al. 2005).

4.2 Effect of foam support surface on the multi-segmented body movement pattern.

The support surface had a clear effect on the multi-segmented movement pattern, as illustrated by marked differences between the body movements recorded while standing on foam and firm surfaces with eyes open or eyes closed, see table 2. While standing on a firm surface, vision reduced the movement at all segments proportionally the same. However, while standing on foam, vision significantly reduced head movements proportionally more than knee movements. We found that, in general, standing on foam increased knee and hip movements proportionally more than shoulder and head movements, both with eyes open and eyes closed. These findings suggest that the shift in the standing movement pattern recorded on foam differs from the common ankle and hip strategy.

Several studies that have used a foam support surface show that trunk movements increase significantly in patients with balance deficits (Gill et al. 2001; Allum et al. 2002; Blackburn et al. 2003). Our study, showing that healthy subjects also increased their hip and shoulder movements while standing on a compliant foam surface, confirms that assessment of trunk movements can provide essential information about postural control. Moreover, our findings also show that the changes in knee movements, due to the different test conditions, were significantly larger than those in the hip and shoulder. Thus, increased trunk sway while standing on foam may not necessarily be a sign of balance deficits. Having uncovered that challenging postural control using the foam support may not only increase the amplitude of body movement but also changes the standing multi-segmented movement pattern, our study will help in distinguishing pathological responses to artificial balance perturbation from those that can be expected also from healthy subjects.

4.3 Effect of foam support surface and vision

The contribution of vision to postural control is well known (Edwards 1946). However, Paulus et al found that visual stabilization decreases with increasing distances to steady visual targets (Paulus et al. 1984). In this study, we observed that vision only significantly reduced the body movements and EMG activity while standing on foam, which concurs with findings in other foam studies (Brandt 1991; Gill et al. 2001; Allum et al. 2002; Blackburn et al. 2003) This supports previous studies showing that unreliable information from the somatosensory receptors increases the reliance on visual and/or vestibular inputs in postural control (Brandt 1991; Rosengren et al. 2007). Moreover, spectral separation analysis showed that vision reduced body movements above 0.1 Hz at all recorded sites while it did not affect the body movements below 0.1 Hz, regardless of position. This finding suggests that some of the increased amount of fast movements while standing on foam with eyes closed can be quickly captured and prevented with eyes open. The recorded torque showed the same pattern as the recorded body movements, in that torques above 0.1 Hz were significantly reduced by vision, especially while standing on foam (while standing on the firm surface, the reduction in movement did not reach Bonferroni corrected significant level of $p<0.01$). Nonetheless, the stability increase induced by visual information could not fully compensate for the conditional changes imposed by standing on foam which concurs with other reports (Brandt 1991).

Of note, there was no statistical evidence that altered support surface conditions and vision had a combined effect on the recorded results, in any of the conditions examined, suggesting that these two factors may act independently on postural control. In contrast, Blackburn et al found a significant interaction of these two factors when analyzing the angular movement of the hip and trunk (Blackburn et al. 2003), so further research is required to investigate the role of vision in postural control.

4.4 Effect of foam support surface and EMG responses

One important result in this study was the demonstration of a clear relationship between multi-segmented body movements and tibialis anterior and gastrocnemius muscle activity. Both tibialis anterior and gastrocnemius muscles have important roles in postural control (Loram et al. 2004). Similar to body movements and torques, EMG activity in the tibialis anterior increased significantly while standing on foam, more consistently when the subjects had their eyes closed. EMG activity in the gastrocnemius muscles also increased on foam, but was unaffected by vision. Since vision reduced, in parallel, both the EMG in the tibialis anterior and the high frequency body movements and torques, while EMG in the gastrocnemius and low frequency torques were unaffected, it may be suggested that the tibialis anterior muscles might have an important role for initiating fast corrective movements whereas the gastrocnemius muscles may be associated with the smooth corrective changes.

This observation partly coincides with results by Loram et al., showing that changes in the gastrocnemius EMG activity only partially correspond to the observed movements of the body center of mass (CoM) (Loram et al. 2005). However, further research is needed to investigate the respective roles of the tibialis anterior and gastrocnemius muscles in human postural control.

4.5 Analysis methods

Our study indicates that spectral separation might be a valuable tool for assessing the contribution of vision in postural control. Notably, the effect of vision on body movements and torque activity found in this study would not have been detected in the statistical GLM analysis without spectral separation, see table 1 and table 3. We therefore recommend the use of spectral separation in future studies of body movements and posturographic recordings.

Standing multi-segmented movement patterns can be assessed and quantified in several ways, and one common method is to measure the movement at each joint (Allum et al. 2001; Nonaka et al. 2002; Gage et al. 2004). In this study, we have analyzed the linear movement patterns and described the differences between trial conditions using quotients. The position markers were attached to the subjects in close correspondence to the body segments to resemble the position of the body’s major joints although this circumstance is not necessary with this analysis approach. It is only essential that the number of markers and the placement of these markers attain sufficient “spatial sampling” of the body movements to conclusively determine the linear movements of the main body segments. Despite the simplicity of the assessment method, clear differences in the linear movement pattern caused by the different surfaces were found in healthy subjects. Hence, the presented assessment and analysis method might be an alternative for those who do not have access to advanced measurement equipment.

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5 References

Allum JH, Adkin AL, Carpenter MG, Held-Ziolkowska M, Honegger F, Pierchala K (2001) Trunk sway measures of postural stability during clinical balance tests: effects of a unilateral vestibular deficit. Gait Posture 14: 227-237

Allum JH, Zamani F, Adkin AL, Ernst A (2002) Differences between trunk sway characteristics on a foam support surface and on the Equitest ankle-sway-referenced support surface. Gait Posture 16: 264-270

Altman D (1991) Practical statistics for medical research. NY: Chapman & Hall, New York

Blackburn JT, Riemann BL, Myers JB, Lephart SM (2003) Kinematic analysis of the hip and trunk during bilateral stance on firm, foam, and multiaxial support surfaces. Clin Biomech (Bristol, Avon) 18: 655-661

Brandt T (1991) Vertigo - Its multisensory syndromes. Springer-Verlag, London

Carlsöö S (1961) The static muscle load in different work positions: an electromyographic study. Ergonomics 4: 193

Edwards AS (1946) Body sway and vision. J Exp Psychol 36: 526-536

Fransson PA (2005) Analysis of adaptation in human postural control. In: Clinical Sciences, Lund. Medical Faculty, University of Lund, Sweden, Lund, p 204

Gage WH, Winter DA, Frank JS, Adkin AL (2004) Kinematic and kinetic validity of the inverted pendulum model in quiet standing. Gait Posture 19: 124-132

Gill J, Allum JH, Carpenter MG, Held-Ziolkowska M, Adkin AL, Honegger F, Pierchala K (2001) Trunk sway measures of postural stability during clinical balance tests: effects of age. J Gerontol A Biol Sci Med Sci 56: M438-447

Jeka J, Kiemel T, Creath R, Horak F, Peterka R (2004) Controlling human upright posture: velocity information is more accurate than position or acceleration. J Neurophysiol 92: 2368-2379

Johansson R, Magnusson M (1991) Human postural dynamics. Crit Rev Biomed Eng 18: 413-437

Johansson RS, Vallbo AB (1980) Spatial properties of the population of mechanoreceptive units in the glabrous skin of the human hand. Brain Res 184: 353-366

Kavounoudias A, Gilhodes J, Roll R, Roll J (1999) From balance regulation to body orientation: two goals for muscle proprioceptive information processing? Exp Brain Res 124(1): 80-88

Kavounoudias A, Roll R, Roll J (2001) Foot sole and ankle muscle inputs contribute jointly to human erect posture regulation. J Physiol 532(Pt 3): 869-878

Kavounoudias A, Roll R, Roll JP (1998) The plantar sole is a 'dynamometric map' for human balance control. Neuroreport 9: 3247-3252

Kristinsdottir EK, Fransson PA, Magnusson M (2001) Changes in postural control in healthy elderly subjects are related to vibration sensation, vision and vestibular asymmetry. Acta Otolaryngol 121: 700-706

Loram ID, Maganaris CN, Lakie M (2004) Paradoxical muscle movement in human standing. J Physiol 556: 683-689

Loram ID, Maganaris CN, Lakie M (2005) Human postural sway results from frequent, ballistic bias impulses by soleus and gastrocnemius. J Physiol 564: 295-311

Nashner LM (1976) Adapting reflexes controlling the human posture. Exp Brain Res 26: 59-72

Nonaka H, Mita K, Watakabe M, Akataki K, Suzuki N, Okuwa T, Yabe K (2002) Age-related changes in the interactive mobility of the hip and knee joints: a geometrical analysis. Gait Posture 15: 236-243

Paulus WM, Straube A, Brandt T (1984) Visual stabilization of posture. Physiological stimulus characteristics and clinical aspects. Brain 107 (Pt 4): 1143-1163

Perry S, McIllroy W, Maki B (2000) The role of plantar cutaneous mechanoreceptors in the control of compensatory stepping reactions evoked by unpredictable, multi-directional perturbation. Brain Res 877(2): 401-406

Proakis J, Manolakis D (1989) Introduction to Digital Signal Processing. Macmillan, New York

Riemann BL, Myers JB, Lephart SM (2003) Comparison of the ankle, knee, hip, and trunk corrective action shown during single-leg stance on firm, foam, and multiaxial surfaces. Arch Phys Med Rehabil 84: 90-95

Rosengren KS, Rajendran K, Contakos J, Chuang LL, Peterson M, Doyle R, McAuley E (2007) Changing control strategies during standard assessment using computerized dynamic posturography with older women. Gait Posture 25: 215-221

Stal F, Fransson PA, Magnusson M, Karlberg M (2003) Effects of hypothermic anesthesia of the feet on vibration-induced body sway and adaptation. J Vestib Res 13: 39-52

Vedel JP, Roll JP (1982) Response to pressure and vibration of slowly adapting cutaneous mechanoreceptors in the human foot. Neurosci Lett 34: 289-294

Williams P (1995) Gray´s anatomy. Churchill Livingstone, Edinburgh, London

Vrancken AM, Allum JH, Peller M, Visser JE, Esselink RA, Speelman JD, Siebner HR, Bloem BR (2005) Effect of bilateral subthalamic nucleus stimulation on balance and finger control in Parkinson's disease. J Neurol 252: 1487-1494

Wu G, Chiang JH (1997) The significance of somatosensory stimulations to the human foot in the control of postural reflexes. Exp Brain Res 114: 163-169

Vuillerme N, Pinsault N, Vaillant J (2005) Postural control during quiet standing following cervical muscular fatigue: effects of changes in sensory inputs. Neurosci Lett 378: 135-139