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Kinematic analysis of the hip and trunk during bilateral stance on firm, foam, and multiaxial support surfaces

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Abstract

Objective. To differentiate hip and trunk motion during double-leg stance.

Design. Trunk and hip angular position variances were measured on different support surfaces with and without vision.

Background. Postural control results from motion about the hips and trunk during bilateral stance. While the hip joint has been studied extensively, information concerning relative amounts of hip and trunk motions during postural control is limited.

Methods. Trunk flexion/extension, trunk lateral flexion, right and left hip flexion/extension and abduction/adduction angular position variances were assessed in 14 normal subjects using an electromagnetic tracking system during bilateral stance on firm, foam, and multiaxial support surfaces with and without vision.

Results. Significantly greater amounts of motion occurred at all joints for the *multiaxial-eyes closed condition* compared to all other surface–vision conditions. No significant differences were found between any other surface–vision conditions. Within the *multiaxial-eyes closed condition*, right and left hip flexion/extension and abduction/adduction magnitudes were significantly greater than those of trunk flexion and lateral flexion, and left hip flexion/extension motion was significantly greater than that of the right hip.

Conclusions. Postural control mechanisms involve similar amounts of motion at the hips and trunk, except for conditions under which a rigid base of support becomes unstable and vision is eliminated.

Relevance

These results suggest that the trunk and hips should be considered separately during kinematic analysis of postural control. This information may be useful in providing a more sensitive assessment of postural control to identify balance-related pathologies associated with stroke, concussion, and somatosensory deficits.

Keywords: Postural control; Postural sway; Limb loading; Limb dominance

1. Introduction

Kinematic variables have been used extensively to describe normal and pathological postural control mechanisms (Horak et al., 1990; Kuo et al., 1998; Diener et al., 1984; Mauritz et al., 1980; Day et al., 1993). Various support surfaces, including firm surfaces (Blackburn et al., 2000; Winter et al., 1993), foam blocks (Blackburn et al., 2000; Guskiewicz and Perrin, 1996; Riemann et al., 1999), and multiaxial platforms (Blackburn et al., 2000; Guskiewicz and Perrin, 1996; Arnold and Schmitz, 1998; Testerman and Vander Griend, 1999), have been used to assess the intricate components of postural control, and the effects of vision on postural control have been well documented (Kuo et al., 1998; Diener et al., 1984; Day et al., 1993; Norre, 1993). The current literature maintains that the hip strategy is an

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important component of postural stability specific to the sagittal plane (Horak et al., 1990; Kuo et al., 1998; Day et al., 1993; Horak and Nashner, 1986), suggesting that hip motion is primarily responsible for postural control in the sagittal plane. Previous research also indicates that postural control in the frontal plane is controlled by motion about the hips serving to load and unload the lower limbs (Day et al., 1993; Winter et al., 1993). Interestingly, the hip and trunk are often considered as one segment for the purposes of motion analysis. However, postural control strategies both in the frontal and sagittal planes result from motions at the hips (i.e. between the leg and pelvis) and at the trunk (i.e. between the vertebral column and the pelvis) (Day et al., 1993; Rietdyk et al., 1999; Horak and Nashner, 1986).

Horak and Nashner (1986) described the hip strategy as a movement pattern designed to correct postural perturbations by creating torques about the hip joint. Their results identified differences between activation patterns of the thigh flexors/extensors relative to the trunk flexors/extensors during forward and backward stance perturbations, suggesting that activation of both hip and trunk musculature is associated with the hip strategy. Kuo et al. (1998) reported that somatosensory information derived from peripheral receptors sensitive to both hip and trunk motion is processed centrally and utilized for generation of the hip strategy, indicating that motion about the vertebral column in addition to motion about the hips is utilized for correction of postural sway in the sagittal plane.

Day et al. (1993) demonstrated that the greatest amount of frontal plane motion during quiet stance occurred between the trunk and upper leg. Winter et al. (1993) suggested that postural stability in the frontal plane is controlled primarily by activation of the hip abductors and adductors designed to alternately load and unload the hips, thereby controlling the center of mass (CoM). Rietdyk et al. (1999) determined that trunk motion in the frontal plane is also involved in controlling the center of pressure (CoP). Based on these previous investigations, it appears as though hip and trunk motion are integral components of postural control in the frontal plane.

Movement of the hips during bilateral stance results in movement of the pelvis based on the articulation between the head of the femur and the acetabulum. As the vertebral column also articulates with the pelvis, trunk motion also results following hip motion during bilateral stance. Kinematic variables provide a wealth of information that helps clinicians to understand and evaluate movement patterns typically associated with various injuries and diseases of the extremities and central nervous system. As such, it is important to understand the natures of these movement patterns with respect to all of the involved joints. This knowledge may then be used to provide a more extensive and appropriate evaluation of the type, severity, and rehabilitation status of the disorder in question. With more information concerning the pathological movement patterns associated with injury and disease, the clinician is better equipped to make decisions regarding return to competitive activity and constraints placed on activities of daily living, as well as the current state in the progression of injury. It is clear that both the hip and trunk play important roles in postural stability, however, current research does not provide a basis for distinction between hip and trunk motion for the purposes of kinematic assessment of postural sway. Therefore, the purpose of the current study was to differentiate hip and trunk kinematics in both the sagittal and frontal planes during bilateral stance on firm, foam, and multiaxial support surfaces.

2. Methods

2.1. Subjects

Fourteen volunteers (7 males, 7 females; height = 1.72 m (SD 0.10), mass = 73.90 kg (SD 15.35); age = 21 yrs (SD 2)) volunteered for participation in the current study. All subjects were free of injury to the lower extremity within 6 months prior to data collection and had no previous history of head injury or vestibular dysfunction. All subjects read and signed an informed consent document which had been approved by the University of Pittsburgh Institutional Review Board.

2.2. Kinematic data collection

All data collection occurred in a single session in the Neuromuscular Research Laboratory at the University of Pittsburgh. Three-dimensional kinematic variables were assessed using the Motion Monitor electromagnetic tracking system (Innovative Sports Training, Inc., Chicago, IL, USA). The primary component of this system is a standard range direct current transmitter containing three orthogonal coils that generate an electromagnetic field. The system also incorporates a series of sensors/receivers which record the electromagnetic flux in the field generated by the transmitter, and convey the signals to a recording computer via hard wiring. The electromagnetic sensors have root-mean-square position accuracy of 1.78 mm/0.5° and a resolution of 0.76 mm/0.1° within a 0.91 m operating range (Innovative Sports Training, Inc., Chicago, IL, USA). Sensor data were sampled at a frequency of 100 Hz and used for the calculation of sensor position and orientation. An electronic hand switch used to mark compensatory events was also sampled at 100 Hz.

Hip motion was operationally defined as occurring between the thigh and the pelvis, while trunk motion was defined as occurring between the vertebral column and the pelvis. Specifically, hip abduction/adduction and hip flexion/extension were compared bilaterally to determine the extent of symmetrical motion. Additionally, these same motions were analyzed relative to trunk lateral flexion and trunk flexion/extension in an attempt to measure the amounts of motion occurring between the thigh and pelvis and between the trunk and pelvis in both the frontal and sagittal planes. Electromagnetic tracking sensors were placed at the level of the C7 spinous process, the base of the sacrum, and the midpoint of each thigh. Hip and knee joint centers were determined by manually digitizing two points on opposite sides of each joint and calculating the midpoint. Hip angle was designated by the sacral sensor, the respective hip joint center, and the respective thigh sensor. Trunk angle was designated by the C7 sensor, the sacral sensor, and the respective hip joint center.

The transmitter was positioned on a custom tripod such that the establishment of a global reference system was possible. The axes of the global reference system were defined such that the X-axis was designated as positive in the anterior direction, the Y-axis was designated as positive to the right of the subject, and the Z-axis was designated as positive inferiorly. These axes were aligned with the cardinal axes of the subject.

Segmental axes of rotation were specified using a joint coordinate system. The use of the joint coordinate system allows for analysis of the kinematic data independent of the order in which the rotations are entered into the matrix calculations (Grood and Suntay, 1983). The orthogonal axes were arranged such that the Z-axis was contained within the trunk or thigh, and reflected trunk rotation and hip internal/external rotation. The Y-axis was defined as being perpendicular to the sagittal plane, allowing hip flexion/extension and trunk flexion/extension. The X-axis was designated as the floating axis, and represented hip abduction/adduction and trunk lateral flexion.

2.3. Procedures

Segmental motion of the thighs, pelvis, and trunk was assessed as subjects attempted to remain motionless while performing a standardized double-leg stance with the medial borders of the feet spaced 20 cm apart and the hands placed on the iliac crests. This position was maintained on firm (FI), foam (FO), and multiaxial (MA) support surfaces under eyes-open (EO) and eyes-closed (EC) conditions. A level tiled floor served as the FI support surface. The FO support surface consisted of a foam block (density = 54.53 kg/m^3), and the Biodex Stability System (Biodex Medical Systems, Inc., Shirley, NY, USA) served as the MA surface. This device is comprised of an unstable platform that allows up to 20° of surface deflection in any direction, and is similar in design to the BAPS (Biomechanical Ankle Platform System, Spectrum Therapy Products, Inc., Jasper, MI, USA) used traditionally in ankle rehabilitation. The relative platform stability is adjustable through eight levels, with level 8 being the most stable. Stability level 6 was used in this investigation. An electronic switch was synchronized with the Motion Monitor which conveyed an analog signal to the collection computer when depressed. Compensatory events that occurred during each trial were noted within the data by depressing the electronic switch for the duration of the event. Compensatory events were defined using the balance error scoring system (Riemann et al., 1999), and included taking the hands off the iliac crests, opening the eyes during the EC conditions, and lifting the heel or forefoot off the support surface.

Kinematic data and data from the electronic switch were reduced using custom software. The custom data reduction program filtered the kinematic data using a 4th order, lowpass, zero phase lag Butterworth filter at 10 Hz, and truncated compensatory event intervals represented by data from the electronic switch. Three 12-s trials were collected and averaged for each surface–vision condition. The middle 10 seconds of data were used for analysis for which the angular position variance was calculated. The orders of surface and vision conditions were randomized to eliminate the potential for an order effect.

2.4. Statistical analysis

Data were analyzed using a three-factor repeated measures analysis of variance (ANOVA) {vision (eyes open, eyes closed) × surface (firm, foam, multiaxial) × motion (right and left hip flexion/extension, right and left hip abduction/adduction, trunk flexion/extension, trunk lateral flexion)}. Statistical significance was established a priori at $\alpha = 0.05$. A Dunn Bonferroni planned contrast procedure was used to identify significant differences within and between conditions using a family-wise error rate of 0.05. In order to simplify the findings, results from the planned contrasts were organized with respect to frontal and sagittal planes.

3. Results

The three-factor ANOVA revealed a significant surface × vision × motion interaction ($F = 7.524$, $P < 0.001$). Angular position variance means and standard deviations for each motion under all surface–vision conditions are presented in Table 1 for the frontal plane and in Table 2 for the sagittal plane.

Table 1
Frontal plane angular position variance means and standard deviations

Condition	Mean (deg)	SD (deg)
FI EO		
RHIP ABD/ADD	0.0127	0.0103
LHIP ABD/ADD	0.0117	0.0126
LAT TRUNK FLEX	0.0318	0.0318
FI EC		
RHIP ABD/ADD	0.0158	0.0166
LHIP ABD/ADD	0.0194	0.0210
LAT TRUNK FLEX	0.0348	0.0410
FO EO		
RHIP ABD/ADD	0.0643	0.0628
LHIP ABD/ADD	0.0522	0.0508
LAT TRUNK FLEX	0.0665	0.0491
FO EC		
RHIP ABD/ADD	0.0934	0.0669
LHIP ABD/ADD	0.1028	0.1028
LAT TRUNK FLEX	0.0763	0.0496
MA EO		
RHIP ABD/ADD	0.7378	1.045
LHIP ABD/ADD	0.7632	1.047
LAT TRUNK FLEX	0.3154	0.4856
MA EC		
RHIP ABD/ADD	35.6340[a,b]	37.4921
LHIP ABD/ADD	35.3240[a,b]	35.5622
LAT TRUNK FLEX	9.9037[a]	6.5786

FI = firm support surface, EO = eyes open, FO = foam support surface, EC = eyes closed, MA = multiaxial support surface.

[a] Significantly different from all other conditions within respective motions ($P < 0.05$).

[b] Significantly different from LAT TRUNK FLEX within MA EC ($P < 0.05$).

3.1. Frontal plane

The Dunn Bonferroni procedure indicated that the angular position variance for all motions was significantly greater for the multiaxial-eyes closed (MA EC) condition when compared to all other surface–vision conditions for the frontal plane (Table 1). No other significant differences were found between surface–vision conditions. Significant differences in angular position variance were also noted between motions within the MA EC condition in the frontal plane. The angular position variances for right hip abduction/adduction (35.63° (SD 37.49)) and left hip abduction/adduction (35.32° (SD 35.56)) for the MA EC condition were both significantly greater than that of trunk lateral flexion (9.90° (SD 6.58)). Right hip abduction/adduction angular position variance was not significantly different from that of left hip abduction/adduction. No other significant differences were present between motions within any of the remaining conditions.

3.2. Sagittal plane

The Dunn Bonferroni procedure also indicated that the angular position variance for all motions was significantly greater for the MA EC condition when compared to all other conditions for the sagittal plane (Table 2). No other significant differences were found between conditions. Significant differences in angular position variance were also noted between motions within the MA EC condition for the sagittal plane. The angular position variance for left hip flexion/extension (16.22° (SD 15.19)) was significantly greater than that of right hip flexion/extension (9.09° (SD 7.32)) for the MA EC condition. Both left and right hip flexion/extension angular variances were significantly greater than that of trunk flexion/extension (2.74° (SD 2.41)). No other significant differences were present between motions within any of the remaining conditions.

3.3. Reliability

A separate set of experiments was performed in 10 individuals (height = 1.77 m (SD 0.08), mass = 77.69 kg (SD 13.41), age = 25 yrs (SD 4)) to assess the reliability of the electromagnetic tracking device using the current protocol. An intraclass correlation coefficient (ICC—equation 2, 1) and associated standard error of measurement (SEM) were calculated to determine the reliability between trials. Each previously described experimental condition was the result of variation of the surface and/or vision component of double-leg stance on

Table 2
Sagittal plane angular position variance means and standard deviations

Condition	Mean (deg)	SD (deg)
FI EO		
RHIP FLEX/EXT	0.0348	0.0353
LHIP FLEX/EXT	0.0358	0.0370
TRUNK FLEX/EXT	0.1561	0.2228
FI EC		
RHIP FLEX/EXT	0.0659	0.0851
LHIP FLEX/EXT	0.0473	0.0510
TRUNK FLEX/EXT	0.1304	0.1435
FO EO		
RHIP FLEX/EXT	0.1306	0.1168
LHIP FLEX/EXT	0.1385	0.1380
TRUNK FLEX/EXT	0.1386	0.1041
FO EC		
RHIP FLEX/EXT	0.1789	0.1629
LHIP FLEX/EXT	0.2155	0.1711
TRUNK FLEX/EXT	0.1687	0.1199
MA EO		
RHIP FLEX/EXT	0.1415	0.1206
LHIP FLEX/EXT	0.1682	0.1707
TRUNK FLEX/EXT	0.2065	0.1653
MA EC		
RHIP FLEX/EXT	9.0864[a,b,c]	7.3214
LHIP FLEX/EXT	16.2235[a,b]	15.1895
TRUNK FLEX/EXT	2.7431[a]	2.4121

FI = firm support surface, EO = eyes open, FO = foam support surface, EC = eyes closed, MA = multiaxial support surface.

[a] Significantly different from all other conditions within respective motions ($P < 0.05$).

[b] Significantly different from TRUNK FLEX/EXT within MA EC ($P < 0.05$).

[c] Significantly different from RHIP FLEX within MA EC ($P < 0.05$).

a firm surface with the eyes open (FI EO). As such, the FI EO condition represents a control condition, and serves as a reference for other conditions. Analysis of between-trial variability during this condition allows for a truer estimate of the reliability of the electromagnetic tracking system using the current protocol compared to the alterations of this condition, which are likely affected to a larger extent by a lack of subject performance repeatability. Therefore, only the FI EO condition was analyzed for reliability purposes. Left hip flexion was arbitrarily chosen as the motion for which the ICC value was calculated within the FI EO condition. The ICC value was low (ICC = 0.31), however, the SEM value was extremely low (0.012°). The Bonferroni procedure we used to determine location of significant differences within the surface × vision × motion interaction prescribes a family-wise error rate for each group of comparisons, specifically for each group of surface–vision-motion combinations in this investigation. The smallest critical value for our data was 2.265, thus the SEM value was well below the level of significance. Therefore, the combination of the ICC and SEM values suggests moderate to high reliability for the electromagnetic tracking system using this protocol.

4. Discussion

The purpose of this investigation was to investigate the similarity between hip and trunk motion in the sagittal and frontal planes during postural sway and subsequent postural control mechanisms. Hip and trunk angular position variances were measured during quiet, bilateral stance. In order to generalize the results of the investigation to testing scenarios widely used in the study of postural sway, three different support surfaces were used, and visual input was altered.

With the exception of the eyes-closed condition on the multiaxial support surface (MA EC), the results of our investigation revealed no significant differences in the quantity of motion occurring at the hips and trunk during quiet, bilateral stance on firm, foam, and multiaxial support surfaces, both in the presence and absence of visual input. The lack of significant differences in joint motion suggests that postural control strategies for both the frontal and sagittal planes involve equal amounts of hip and trunk motion. This trend of similar hip and trunk motion utilized for postural control was consistent across all surface–vision conditions, except MA EC for which hip motion exceeded that of the trunk. The types of support surfaces utilized in this investigation have been used extensively in the literature (Diener et al., 1984; Blackburn et al., 2000; Guskiewicz and Perrin, 1996; Rietdyk et al., 1999; Winter et al., 1993; Riemann et al., 1999; Arnold and Schmitz, 1998). Additionally, postural sway has been assessed by numerous authors under eyes-open and eyes-closed conditions (Kuo et al., 1998; Diener et al., 1984; Day et al., 1993; Norre, 1993). Because all testing scenarios, with the exception of MA EC, produced equal magnitudes of hip and trunk motion, it appears as though separate analyses of hip and trunk motion would provide a more representative depiction of postural sway kinematics. Previous literature suggests that postural control strategies within both the frontal and sagittal planes are achieved through a combination of hip and trunk motions (Day et al., 1993; Horak and Nashner, 1986). Data from the current investigation not only confirm these speculations, they also suggest that trunk motion plays a role in postural control that is equally as important as that of the hip. In that the magnitudes of trunk and hip motions are similar during bilateral stance, a narrowed focus on a single kinematic contributor to postural control mechanisms may limit the application of kinematic analysis of postural control.

When using kinematic analysis to identify characteristic movement patterns associated with trauma and pathology, it is advantageous to analyze the complete system, or the major contributors therein, in order to obtain the most sensitive, objective measures of postural control. Relevant examples of this concept include concussion and stroke. The literature maintains a direct relationship between highly specialized regions of the cerebral cortex and muscle activation at specific joints (Jancke et al., 2000; Rao et al., 1993). The presence of increased hip or trunk motion following concussive or cerebro-vascular trauma as evidenced by kinematic analysis may provide a more efficient means of locating injury sites with respect to alterations in joint motion based on mapping of the cerebral cortex.

Winter et al. (1993) suggested that a relationship was present between postural control in the frontal plane and loading/unloading of the lower extremities through hip abduction/adduction during double-leg stance. These authors demonstrated an antiphase relationship between right and left limb CoP, indicating loading/unloading of the lower extremities. In a separate paper, Winter et al. (2003) concluded that the CoP was controlled in the antero-posterior direction via the ankle musculature, while medical/lateral CoP movement was controlled by the hip abductors/adductors. The lack of significant differences between hip abduction/adduction and trunk lateral flexion in our data suggests that trunk motion is also an important component of strategies utilized to load and unload the lower extremity for postural control in the frontal plane, as trunk motion was equal to that of the hip. Lateral motion of the hips during bilateral stance (i.e. hip adduction coupled with contralateral hip abduction) associated with loading/unloading of the lower limbs necessarily results in trunk lateral flexion to the side opposite the lateral hip shift (Rietdyk et al., 1999). Movement of the pelvis in the direction of hip adduction results in movement of the CoP in the same direction. In order to maintain the body's center of gravity within its base of support (i.e. maintain balance), coincident trunk lateral flexion opposite the hip adduction must occur, serving to limit movement of the CoP. Our data suggest that kinematic analysis of the hip alone may not provide an accurate picture as to the relevant contributions of the anatomy proximal to the hip joint to postural control in the frontal plane. These results again emphasize the need to assess hip and trunk kinematics for the investigation of postural control during bilateral stance, as both play integral roles in controlling postural sway.

The results of the current investigation for the MA EC condition were somewhat surprising. When a rigid support surface became unstable and vision was eliminated, large significant increases in the motions of all joints occurred. In the frontal plane, the magnitudes of both left and right hip abduction/adduction were significantly greater than that of trunk lateral flexion. In the sagittal plane, the magnitudes of both left and right hip flexion/extension were significantly greater than that of trunk flexion/extension. Overall increases in joint motion are to be expected, as the subject no longer has a stable surface to exert postural control mechanisms against in order to correct postural sway, and visuospatial information is eliminated. However, a significantly greater amount of left hip flexion/extension occurred during the MA EC condition when compared to right hip flexion/extension. This discrepancy may allude to a potential role for limb dominance in postural control.

The MA surface is designed such that lateral loading (i.e. shifting weight between limbs in the frontal plane) is achieved through knee and hip extension of the loaded limb, with coincident knee and hip flexion of the relatively unloaded limb. This alteration in joint position is achieved through the rigid composition of the platform, and the presumption that the platform operates as a system of 1st class levers oriented radially about a single pivot point. For example, if the subject loads the right limb by shifting his weight in the frontal plane, the right knee and hip will remain in extension and the right side of the platform will be depressed. Conversely, the left side of the platform will be forced upward, resulting in knee and hip flexion of the left limb. Our data indicate that loading of the right limb occurred, resulting in a greater amount of left hip flexion/extension as compared to that of the right hip. The presence of a greater amount of left hip flexion/extension may indicate a tendency for loading of the dominant limb to maintain balance under specific conditions. Unfortunately, we did not assess limb dominance in our investigation. These results warrant further investigation of the role of limb dominance in postural control.

5. Conclusions

Postural control during bilateral stance appears to be achieved via both hip and trunk motion. The results of our investigation suggest that the amount of motion occurring at the hips and trunk with respect to the pelvis is essentially the same magnitude on a variety of support surfaces, with the eyes either opened or closed. Hip and trunk motion remained similar until a rigid base of support was no longer fixed and the eyes were closed. Because magnitudes of hip and trunk motion were similar, it cannot be assumed that motion of one segment contributes more to postural control than the other. These findings emphasize the need for separate kinematic analyses of the hip and trunk during bilateral stance to assess postural control strategies. Assessment of hip kinematics alone to identify pathological postural control may fail to identify markers of injury observed in trunk kinematics. By allowing for a more complete depiction of pathological motion, kinematic analysis of the hip and trunk would better prepare the clinician for evaluation of injuries that impact postural control. Future research is necessary to determine the role of the trunk in postural control, and of trunk kinematics for predicting postural pathology.

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