Center of pressure excursion capability in performance of seated lateral-reaching tasks

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Received 19 November 2003; accepted 5 August 2005

Abstract

Background. Seated center of pressure excursion capability can be used for patient evaluation in a clinical setting and in universal design. A quantification of excursion capability across age and anthropometry has not been previously reported, although some research suggests that the ischial tuberosities are the support structure limiting the excursion.

Methods. Thirty-eight neurologically healthy adults ranging in age from 21 to 74 years and including 12 obese persons performed a series of 6 lateral-reaching tasks. Participants sat on a platform such that their feet did not touch the ground, leaving their legs free to provide counterbalancing support. Data recorded from a force plate under the platform allowed calculation of the center of pressure throughout the trial and the maximum excursion for each condition was recorded.

Findings. The average excursion capability for the healthy, experimental population was 148 mm or 37% of seated hip breadth. Taller participants had larger maximum excursions, on average, than shorter participants, and older participants had smaller excursions than younger participants.

Interpretation. The greater trochanter of the femur—rather than the ischial tuberosities—appears to be the primary support structure limiting center of pressure excursion in lateral, balance-limited reaches without contralateral support. These measures and concepts can be used for design, accommodation, and clinically for patient assessment.

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Keywords: Seated balance; Aging; Postural control; Lateral reach

1. Introduction

Balance is maintained through a complex interaction of the various components of the vestibular, nervous, and musculoskeletal systems (Konrad et al., 1999). Many factors can affect balance-maintenance capability, including disease (van Wegen et al., 2001), environmental motion (e.g., in a car or boat) (Kamper et al., 1999a,b), or injury (Potten et al., 1999). Similarly, certain neurological conditions have been found to reduce balance capabilities (Keenan et al., 1984; Nichols et al., 1996). Age has been shown to impact balance-limited, seated lateral reach capability significantly (Campbell et al., 2001; Kozak et al., 2003). Beginning between 30 and 40 years of age, the balance-limited lateral reach distance (maximum distance reached by fingertip in a lateral reach) decreased in one population by 4 mm per year (Campbell et al., 2001).

This paper uses dynamic center of pressure (CoP) excursion measured using a force plate as an indicator of balance capabilities. The applicability of this method of CoP excursion measurement has been established in both seated and standing conditions (Holbein and Chaffin, 1997; Kollmitzer et al., 2002). Prediction equations
quantifying standing balance capability in terms of CoP excursion were developed by Tanaka et al. (1999), using experimental data. The relationship between reach, balance, and CoP excursion has been studied under many conditions in seated environments as well (Chaffin and Woolley, 2001; Cholewicki et al., 2000). Similar studies have been performed for specific populations. In an experiment involving standing participants, older participants did not move their CoP as far as the younger ones and they also moved to their limit more slowly (Kozak et al., 2003). The researchers hypothesized that they did this so that they could ease into their limit and not lose their balance. Seelen et al. (1998) and Chaffin et al. (2004), found that people with a thoracic-level spinal cord injury had a reduced capacity for moving their center of pressure, which translated into a reduced reach capability. Kerr and Eng (2002) demonstrated the repeatability of this type of measure—an essential attribute for clinical and design purposes.

Quantifying balance-maintenance capability through balance-limited reaches is also useful to those involved in rehabilitation. Diagnostic relationships, such as those between standing lateral balance capability and risk of fall in the elderly (Rietdyk et al., 1999), can be determined once a performance baseline exists. Quantification of this capability may lead to more accurate predictions of functional outcome as well as providing a metric that can be used to quantify rehabilitation progress (Carr et al., 2000; Korner-Bitensky et al., 1989; Lynch et al., 1998; Nichols et al., 1996; Sandin and Smith, 1990).

Stability zones or stability limits describe the in-balance limits of a person while they are seated or standing. In analysis of standing balance, these regions are defined relative to the feet, which provide the base of support within which the CoP must reside for static balance to be maintained. While the entire area from heel to toe and laterally from outside of the left foot to the outside of the right foot is hypothetically this base of support, it is functionally much smaller. Experiments by Holbein and Redfern (1997) showed that the functional stability limits are actually an area of about 50–60% of the theoretical limits.

For seated environments, the limits are more difficult to define since the body uses different mechanisms for maintaining balance depending on the direction of CoP excursion. Additionally, the seat itself affects stability since a seat-back and/or side-bolsters limit excursion rearward and laterally. Chaffin and Woolley (2001) and Chaffin et al. (2004) hypothesized that the seated base of support was restricted, when not encumbered by the seat, laterally by the location of the ischial tuberosities (IT) and rearward by the coccyx. Pelvis geometry from Reynolds et al. (1981) can be used to calculate an IT breadth that is the hypothesized functional stability limit for seated near-lateral reaches. Subsequent sections of this paper will compare these theoretical results against the results obtained experimentally in our study.

Seated, forward-reaching tasks are not addressed in this paper since the legs provide support as the CoP shifts forward. The net result is that forward reaches are more likely to be limited by upper-body strength or range of motion than balance (Chaffin et al., 2004; Curtis et al., 1995; Dean et al., 1999a,b). Forward-reaching tasks can be balance-limited for some populations, however (e.g., those with spinal cord injury) (Chaffin et al., 2004; Seelen et al., 1998). While these populations will not be addressed specifically in this work, the tools and methods developed here are intended to be helpful for analysis and design of accommodating environments.

The objectives of the current study were (1) to obtain normative data on CoP excursion capability for lateral and near-lateral reaches, (2) to assess the relationships between participant descriptors and CoP excursion capability, and (3) to test the hypothesis that the ischial tuberosities are the primary support structure and limiting factor in CoP excursion during lateral seated reaches. A heterogeneous sample of healthy people was used with the expectation that the empirical results would be typical of those found in a broad population. Participants were selected to represent a wide range of ages (21–74 years of age) and body sizes—including a large sample of obese participants (approximately 30%).

2. Methods

Participants sat on a rigid, instrumented platform and performed maximal, volitional, horizontal reaches directed either laterally (0°), 30° forward, or 30° rearward of lateral (Fig. 1). They were instructed to reach at a comfortable speed as far as they could and hold the final posture for 5 s. Each reach trial was performed twice, for a total of six trials per participant. Trials were paced to avoid fatigue and each participant could request additional rest. The platform was placed high enough that the participants were unable to rest their feet on the ground, leaving them free to swing their legs to maintain balance. This condition was selected (versus one in which participants rested their feet on the floor) for several reasons. First, a previous experiment performed by Kerr and Eng (2002), used a similar condition in a study focusing on older participants (mean age 64.9 years) and replicating their condition allowed some comparison of results (although Kerr and Eng measured reach distance rather than CoP excursion). Second, when the feet are able to make contact with the floor, this increases the number of counterbalancing options available to the sitter. Suspended on the seat, participants were restricted in how they could use their legs to counterbalance. Though this condition is not typical
of seated reaches, it can be easily replicated and therefore could be useful in a clinical setting. Moreover, the legs-suspended condition facilitates the current investigating by limiting the base of support to the area under the buttocks and thighs.

The seat platform was located 85 cm above the ground. A thick pad to the right of the participants protected them in the event of a loss of balance. A pressure-sensitive mat (XSensor, Inc., Calgary, Canada) was fixed on the platform and used to identify the approximately location of the ischial tuberosities, which produce pronounced peaks in the pressure distribution. The 0° azimuth was defined by the line connecting these peaks so that the location of each participant’s pelvis relative to the platform was consistent. A 5-mm-thick piece of open-cell foam was placed between the sensor pad and the plywood surface of the platform. The platform was rigidly attached to a force plate (OR6-5-1, AMTI, Watertown, MA, USA) which was instrumented to report the vertical force and the moments about the horizontal axes, providing a direct means of estimating the CoP location during the reaches. Forces and moments from the force plate were recorded by a computer at 18 Hz for approximately 6 s. The data from the pressure pad was recorded on the computer over the duration of the trial.

Twenty men and eighteen women participated in the study. They ranged in age from 21 to 74 years with a median age of 36. The mean stature was 1.69 m with a range of 1.41 m (<5th percentile female for the US population) to 1.88 m (95th percentile male). Body mass ranged from 50 to 133 kg with a mean of 84.1 kg. The mean body mass index (BMI) for the group was 28.9 kg/m², with a range of 18.9–43.5 kg/m². All participants were neurologically healthy and paid volunteers. Volunteers were accepted based on their age (all volunteers older than 30 years of age were accepted), gender (an even number of males and females was desired) and body sizes (desired more than 30% to be obese). Forty-three anthropometric dimensions were recorded for each participant according to a protocol established in the Human Motion Simulation Laboratory at the University (Woolley, 2001). The experimental procedures were approved by an Institutional Review Board at the University of Michigan and all participants provided informed consent.

For each trial, the CoP excursion in the lateral direction was calculated by dividing the horizontal moment by the vertical force. The initial location of the CoP was subtracted from the entire trajectory making it relative to its initial location, which was approximately the midsagittal plane of the erect torso. The CoP excursion trajectory was processed through a fourth-order, low-pass, zero-phase-lag discrete Butterworth filter with a 5 Hz cutoff frequency. Participants were tested in each trial condition twice, and the results from the trial with the larger excursion were used for the analysis. The greatest measure was chosen since the purpose of the experiment is to measure the maximum CoP excursion capability.

The CoP excursion data were analyzed to determine the effects of reach direction and participant characteristics on the maximum excursion. Analysis of variance (ANOVA) and post-hoc contrast tests were used to test
differences in mean excursion across reach directions. The stepwise linear regression procedure in JMP software (SAS Institute, Cary, NC) was used to assess the influence of participant descriptors on maximum CoP excursion.

3. Results

In all trials, the participants chose to swing their legs to the left, opposite the direction of reach. Fig. 2 shows the maximum CoP excursion for all trials (38 maxima for each of three azimuths). The 5th (71.9 mm), 50th (148 mm), and 95th (197 mm) percentile capabilities are marked. These values, superimposed on a 50th percentile male pelvis, are shown in Fig. 3.

If the lateral limit of CoP excursion was defined by the location of the ischial tuberosities, the maximum lateral excursion would be approximately 44 mm (half of the typical ischial tuberosity spacing of 88 mm) (Reynolds et al., 1981). In the current study, the CoP excursion exceeded 44 mm in every trial. It was observed that participants rolled their pelves laterally, thereby increasing their functional base of support toward the greater trochanter of the femur. Consequently, the data were normalized by each participant’s seated hip breadth, producing the second histogram in Fig. 2, with the 5th (0.16), 50th (0.37), and 95th (0.51) percentile capabilities indicated. The greatest normalized CoP excursion capability (CoPnorm) was approximately 3 times larger than the smallest, indicating a broad range in capability across participants.

Trials were performed in three different reach directions or azimuths: +30°, 0°, −30°. The mean normalized excursions were 0.338, 0.376, and 0.378 in the −30°, 0°, and +30° directions, respectively. Using normalized excursions as the dependent measure and azimuth as a fixed factor in ANOVA revealed a significant difference among azimuths (F_{2,111} = 2.47, p = 0.09). Post-hoc contrast tests showed that the mean normalized CoP excursion in the rearward, −30°, direction was significantly different from the +30° and 0° trials (F_{1,113} = 4.98, p = 0.028).

Stepwise linear regression was used to investigate the relationships between participant characteristics and normalized CoP excursion. Potential continuous predictors were stature (erect standing height), hip breadth, arm length, age, and body mass index (BMI). Body mass index was calculated as the participant’s mass in kg divided by stature in meters squared. Azimuth was included as a fixed categorical effect at two levels: −30° and the pooled 0°, and +30° directions. All potential two- and three-way interactions were available for inclusion. The stepwise procedure was executed with p ≤ 0.25 to enter and p ≥ 0.10 to leave.

The stepwise analyses yielded four significant predictors (in order of significance): Age (F_{1,109} = 31.7, p < 0.0001), HipBreadth (F_{1,109} = 30.1, p < 0.0001), Stature (F_{1,109} = 11.2, p = 0.001), and the combined direction of reach, Azimuth (F_{1,109} = 10.0, p = 0.002). No two- or three-way interactions among potential predictors were found to be significant (p > 0.05 in all cases). Equation (1) is the linear model predicting the CoP excursion capability normalized by hip breadth,
Regression analyses demonstrated that normalized CoP excursion was significantly related to reach direction, stature, and age. Excursion capability was greater for more-forward reaches, probably because the effective base of support extended forward under the thighs. Taller participants had slightly larger excursion capability, on average. Interestingly, hip breadth was negatively associated with excursion capability even after normalizing for hip breadth. That is, participants with larger hip breadths were capable of smaller maximum excursions, on average, as a fraction of hip breadth. The standard anthropometric measurement of seated hip breadth sums the bony bitrochanteric breadth and the soft-tissue margin over the trochanters. In this data set, in which 30% of the participants were obese, the variance in hip breadth is probably due primarily to flesh margin, rather than to differences in bitrochanteric breadth. Hence, dividing by seated hip breadth tended to reduce the normalized maximum CoP excursion capability of people with larger amounts of soft tissue. This finding suggests that normalizing to hip breadth can produce a misleading evaluation of balance capability. Normalizing to bitrochanteric breadth, a measure obtained by compressing the tissue over the trochanters with a standing pressing the tissue over the trochanters with a standing.

The excursion capabilities of the older participants are similar to those reported by Kerr and Eng (2002) in a related experiment. They measured a CoP excursion capability of 125 mm for their participant pool with an average Age of 64.9 years and an average Stature of 1660 mm. The regression model from the current study (Eq. (1)) can be used with the average participant characteristics from the Kerr and Eng (2002) study and Azimuth = 0 (their approximate experimental condition) and the mean HipBreadth from this participant pool (407 mm). This results in a predicted mean excursion capability of 124 mm for a lateral reach, remarkably close to the Kerr and Eng result.

4. Discussion

This study demonstrated that the base of support for lateral seated reaches substantially exceeds proposed limits defined by the ischial tuberosities (IT). Instead, the greater trochanter of the femur appears to provide substantial support as a persons pelvis rolls in the direction of the reach. The measured CoP excursion in all trials exceeded the 44-mm limit estimated using half of the midsize-male IT spacing of 88 mm (Reynolds et al., 1981). Recognizing the contribution of the lateral hip area to the base of support, the CoP excursions were normalized by seated hip breadth in subsequent analyses.

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\[ CoP_{\text{norm}} = 0.54 + 1.69 \times 10^{-4} \text{Stature} - 2.55 \times 10^{-1} \text{Age} - 9.18 \times 10^{-4} \text{HipBreadth} + 0.020 \text{Azimuth}, \]
This work confirms the clinical observations (Campbell et al., 2001; Rietdyk et al., 1999) that CoP excursion capability is smaller in older people. The participants in the current study were relatively fit. The age effect in a population that included a more representative sample of older participants might be larger.

This paper provides normative data on lateral reach CoP excursion capability that could be used to guide clinical application of this technique. A clinical finding that an individual’s CoP excursion was substantially less than would be expected for a person of similar age and stature might be a useful diagnostic tool. Similarly, tracking an individual’s CoP excursion capability might provide a valuable quantitative metric to gauge the effectiveness of therapies meant to improve reaching.

5. Conclusions

While standing, people are only able to move their CoP within a fixed base of support, defined by the placement of the feet. Research in standing balance has shown that the functional stability limit lies well within this area. In seated balance, the base of support is not as clearly defined since the pelvis rolls as the sitter leans in the direction of the reach. Previous estimates of this base of support have supposed that the ischial tuberosities define the boundary of maximum CoP excursion in lateral reach or loading scenarios. The present study has shown that when a person’s legs are free to swing, the anatomical base of support may extend all the way out to the upper trochanter of the hip. Based on these results, two new models are presented. The first details the CoP excursion capability for participants performing a seated lateral reach where only the free movement of their lower limbs can provide counterbalancing support. An estimate of the 5th, 50th, and 95th percentile population capabilities are given. In the second model, the average excursion capability for a particular participant with a known stature, age, and reach direction is predicted by regression. Both of these can be utilized by designers to investigate the need for external counterbalancing supports (such as handles) in the performance of a particular task, or redesign of the reach task requirements.

The current study examined only a small range of seated reach behavior. Subsequent studies of these issues would benefit from the inclusion of more participants over 50 years of age. The study methodology could be readily extended to include additional counterbalancing strategies such as bracing with the legs or use of a support by the contralateral hand. Additional work in handle-assisted reaches should investigate the effect of strength and range of motion on participant capability.

References


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