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RESEARCH ARTICLE

Postural Asymmetries in Response to Holding Evenly and Unevenly Distributed Loads During Self-Selected Stance

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ABSTRACT. The authors examined postural asymmetries during quiet stance and while holding evenly or unevenly distributed loads. Right-hand dominant subjects preferentially loaded their right lower limb when holding no load or a load evenly distributed in both hands, but no differences in center of pressure (CoP) were observed between the left and right limbs. However, longer CoP displacement was observed under the preferentially loaded limb, which may reflect a functional asymmetry that allows quick movement of one limb in response to a potential perturbation. When a load was held only in the nondominant hand, sample entropy decreased in the left (loaded) limb but increased in the right (unloaded) limb, suggesting the unloaded foot compensated for a loss of control flexibility in the loaded foot.

Keywords: asymmetry, center of pressure, postural adaptations, posture

Broca (1865) first discovered the existence of asymmetry in the human brain when he demonstrated laterality in language function. Early neurological studies suggested that this laterality was an ontogenetic property only observed in humans and the great apes. It was thus inferred that cerebral hemispheric dominance was a trait necessary for high-level cognition. Functionally, right–left brain asymmetries have been attributed to many of the higher brain functions seen in humans, including musical ability, language, visual-spatial abilities, and emotion (Galaburda, LeMay, Kemper, & Geschwind, 1978). Delacato (1966) proposed a theory that proper sensorimotor control would only occur if one side of the brain dominated over the other. This theory suggested that brain asymmetries are functional and predicted that many intellectual problems were related to cerebral symmetry (Delacato). Recently, certain lateralities have been found in lower vertebrates. For example, cerebral asymmetries have been found to aid in object recognition and visual discrimination in pigeons (Gunturkun et al., 2000).

Although long known in the neuroscience literature, the idea that asymmetries can be functional has only recently gained popularity in the motor behavior literature. In human walking, healthy individuals typically adopt locomotor patterns that are not symmetric (Haddad, Van Emmerik, Whittlesey, & Hamill, 2006; Hirokawa, 1989; Sadeghi, Allard, & Duhaime, 1997; Sadeghi, Allard, Prince, & Labelle, 2000). Hirokawa suggested that the right limb's primary function was to provide a propulsive force during midstance. Conversely, the left limb's primary function was that of support (Hirokawa; Sadeghi et al., 1997; Sadeghi et al., 2000). Laterality differences have also been observed in quadrupeds. For example, horses adopt an asymmetrical gait when galloping as a strategy to better withstand increases in mechanical stress (Deuel & Lawrence, 1987). Further, trained horses have been shown to have greater levels of asymmetry than untrained horses (Drevemo, Fredricson, Hjerten, & McMiken, 1987). Functional asymmetries between the limbs have also been observed during bimanual tasks (Goble & Brown, 2008; Guiard, 1987). Guiard proposed that when performing bimanual tasks, the left (or nondominant) hand serves to control or stabilize the action while the right hand serves to generate the movement and perform the manipulative action. In the locomotion and bimanual object manipulation examples discussed previously, it appears that motor asymmetries allow each limb to perform different aspects of the overall task. This functional division of labor ultimately allows the task to be performed more effectively, efficiently, and accurately.

Extensive research has examined postural asymmetry in individuals with various pathologies (e.g., Lomaglio & Eng, 2005). Typically, these studies assume asymmetry is detrimental to balance control. Alternatively, it has been suggested that, similar to gait, postural asymmetries may be functional. To date, only a handful of studies have examined postural asymmetry in healthy young adults (Anker et al., 2008; Aruin, 2006; Blaszczyk, Prince, Raiche, & Hebert, 2000; Genthon & Rougier, 2005; Hesse, Schauer, & Jahnke, 1996; Sackley & Lincoln, 1991), and these studies typically only examine asymmetry in weight distribution. Little work has examined asymmetries that are present in the center of pressure (CoP) characteristics between the right and left limbs (Anker et al.; Genthon & Rougier). More comprehensive research in healthy young adults is needed to determine if lower limb asymmetries are typically adopted to enhance postural performance. These findings can be extended to help understand whether asymmetries present in patients with unilateral disorders are a consequence of or an adaptation to the disorder.

In general, postural symmetry research in healthy young adult populations has found that postural stability decreased when subjects were asked to shift varying amounts of their body weight to one side (Anker et al., 2008; Genthon & Rougier, 2005). Further, CoP displacement increased more under the unloaded foot than the loaded foot (Genthon &

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Rougier). These changes were ascribed to decreased efficiency of the hip load and unload mechanism (Anker et al.; Genthon & Rougier) and increased ankle moments (Anker et al.). These studies therefore suggested that asymmetries from self-induced weight shifting are not functional and do perhaps lead to postural instabilities. In a perturbation study, anticipatory postural adjustments (APAs) were modified (45° external rotation) based on leg rotation asymmetry (Aruin, 2006). The contralateral limb also showed increased APAs as measured by EMG. Therefore, at least in asymmetrical conditions, it is evident that the limbs contribute differentially to the control of balance.

In addition to observed postural asymmetries during self-induced weight shifting, previous researchers have shown that young healthy subjects put 52% of their weight on one limb (percentage calculated from lower limb asymmetry score) during a quiet standing task with eyes open (Blaszcyk et al., 2000). This observed asymmetry in weight distribution appears to increase with age (Blaszcyk et al.; Sackley & Lincoln, 1991). However, it is still not clear if the limbs are used differentially to control balance in a self-selected posture during standing. In the present study we further explore this self-selected limb load asymmetry by examining the CoP characteristics under each limb with two adjacent force plates. In addition, it is important to expand postural asymmetry research to examine how individuals adapt to an externally imposed asymmetry from holding a load with one hand. Because load carriage is a common task (e.g., carrying a bag of groceries), this paradigm may yield insight into the adaptations that occur in many activities of daily living.

In the present study, we used a variety of traditional and nonlinear analytical techniques to quantify postural adaptations during each of the conditions. Specifically, in addition to CoP standard deviation (CoP_{SD}) and path length (CoP_{PL}), postural time to contact (TtC) and sample entropy (SampEn) were assessed. Postural TtC was defined as the time it would take the CoP, given its instantaneous position, velocity, and acceleration, to contact the base of support if no corrective actions were taken. TtC provides a temporal measure of postural stability relative to the individual's stability boundaries at each instant in time. SampEn provides information regarding the complexity of the CoP signal by examining the time dependent fluctuations of the time series. Entropy measures differ from traditional techniques because the dynamics of the signal are assessed on a moment-to-moment basis rather than summarized over the time series (Rhea et al., 2011; Richman & Moorman, 2000). For example, a CoP signal that is very regular (almost sinusoidal) may have the same mean and standard deviation as a complex (irregular) signal. However, the dynamics of these signals are very different and can only be captured using a more complex analysis (Rhea et al.). Previous research has suggested entropy measures, such as SampEn, provide information regarding the adaptability and flexibility of the postural system that cannot be captured using more traditional postural measures (Haddad, Van Emmerik, Wheat, & Hamill, 2008; Roerdink et al., 2006). For example, the loss of complexity hypothesis has proposed that complex systems become more regular (less complex) with aging and disease (Lipsitz & Goldberger, 1992). In human motor behavior, a loss of complexity may signify that less of the body's independent degrees of freedom (e.g., muscles, joints, motor units) are recruited to complete a task. This strategy results in movements that are less flexible and adaptable. In the present study, SampEn measures were used to examine if subjects differentially control the dynamics of each leg to adapt to the added constraint of carrying a load.

The first purpose of this study was to examine if postural asymmetries are evident in a self-selected quiet standing posture of young healthy adults. Based on the fact that asymmetries are found in weight bearing, the neuromuscular system, and various aspects of motor behavior (e.g., gait and manual control), we hypothesized that differences would be present between the right and left limbs during unloaded self-selected stance. However, relative to walking, standing has smaller segment displacements and accelerations and therefore requires smaller muscle contractions, so the task of standing may not be challenging enough to reveal functionally relevant asymmetries. Therefore, in the second and third purposes (further discussed subsequently) we examined functional asymmetries and adaptations that result from holding evenly or unevenly distributed loads. *Functional asymmetry* was defined as the right and left limbs exhibiting different behaviors while holding an evenly distributed load. *Adaptation to asymmetry* was defined as right and left limbs exhibiting different behaviors while holding an unevenly distributed load.

The second purpose of this study was to examine functional postural asymmetries between the right and left limbs that occur as an evenly distributed static load (0.5–4.5 kg) was held in each hand. Given recent findings in the gait and manual control literatures, it was hypothesized that individuals would demonstrate left or right asymmetries as the evenly distributed weight load increased. Such a finding would suggest that balance asymmetries are indeed functional, and as the difficulty of the task increases, the right and left limbs contribute differently to overall balance control.

The third purpose of this study was to examine postural adaptations that occur as a static load (1–9 kg) was held in the nondominant hand to create an externally imposed asymmetry. We hypothesized that the right and left limbs would demonstrate different adaptations as load magnitude increased.

Method

Subjects

Twenty-two right-handed college-aged (M age $= 24 \pm 3.2$ years; 12 men, 10 women) subjects were recruited from the university undergraduate community. All subjects were free from any sensory and neuromuscular disorders that could impede postural control. On entering the lab, experimental procedures were fully explained and an informed consent form was signed (approved by the university institutional review board).

Experimental Setup

Bilateral CoP data were collected at 200 Hz using two AccuSway force platforms (AMTI). The two force plates were placed next to each other with a 1.8 cm gap between them. In all trials, subjects were required to hold an asymmetrical load in their left (nondominant) hand, or a symmetrical load equally distributed in both hands. Hand dominance was determined as the hand the subject used to write. Hand dominance was examined, rather than lower limb dominance, because the task required the subject hold a load with the upper limb(s).

The weights consisted of a plastic bucket (height = 24 cm, circumference = 69 cm) filled with sand bags. The handle of the bucket was wrapped with tennis racket grip tape to improve comfort. The accuracy of the weights was confirmed prior to each trial using a pediatric strain gauge scale accurate to 10 grams. The specific loads held by the subjects were 1, 3, 5, 7, and 9 kg. In the evenly distributed conditions half of the load was held in each hand. In the unevenly distributed conditions, the entire load was held in the nondominant (left hand). Ten unique trials were therefore performed (5 evenly distributed load trials and 5 unevenly distributed load trials). Each trial was performed two times, yielding a total of 20 load trials. In addition to the load trials, two quiet-stance trials were performed, in which subjects were instructed to stand with their arms by their side; these trials were called the unloaded trials.

Procedures

Subjects were instructed to step onto the force plates so that one foot was on each plate. No detailed instructions were given regarding how to stand. Rather, subjects were simply asked to adopt a stance they could comfortably maintain while holding a weight. Once on the force plates, the experimenter placed tape around the perimeter of the feet. This tape was used to ensure that subjects adopted the same stance orientation after each rest period. The tape was also used to determine the coordinates of the subject's base of support, which were later used to calculate postural TtC. To negate the possibility that different footwear could influence the results, all trials were performed barefoot.

Before each trial, the weighted bucket(s) were placed in front of the force plates. The subject stepped onto the force plates so that each foot was within the previously marked boundaries. The experimenter then handed the subject the bucket(s) and stepped out of his or her field of view. After grasping the buckets, the subject was instructed to let the bucket freely hang (not to rest the bucket on the thigh). Due to holding the load, the shoulder was more abducted in loaded than unloaded conditions. Therefore, any observed differences across unloaded and loaded conditions (Hypothesis 2, see subsequent analysis) must consider the possible influence of arm position. The subject was also instructed to visually fixate on a black dot that was placed at eye level (150 cm away). These instructions were provided to ensure that all subjects adopted a similar approach to holding the buckets. One major goal of this study was to gain an understanding regarding how balance is maintained as individuals hold a load, a common daily task. Thus, to increase the ecological validity of the study, no other instructions were given to the subjects to avoid unduly constraining their behavior. At this point, force plate data were collected for 30 s. At the end of the 30-s trial, the subject handed the weights to the experimenter. All loaded and unloaded trials were presented in a random order. After every three trials subjects were given a 3-min rest break.

Data Analysis

The local coordinate system of each force plate was transformed so that origin of the global coordinate system of the two force plates was located at the back left-hand corner of the left force plate. Net CoP was then calculated as the weighted average of the CoP from the left and right force plates using Equation 1 (Winter, Patla, Ishac, & Gage, 2003).

$$\mathrm{CoP_{Net}} = \frac{\mathrm{CoP_L} \times \mathrm{F_{zL}}}{\mathrm{F_{zL}} + \mathrm{F_{zR}}} + \frac{\mathrm{CoP_R} \times \mathrm{F_{zR}}}{\mathrm{F_{zL}} + \mathrm{F_{zR}}} \quad (1)$$

In which $\mathbf{F_{zL}}$ and $\mathbf{F_{zR}}$ represent the vertical ground reaction forces from the left and right force plates, respectively. $\mathrm{CoP}_\mathbf{L}$ and $\mathrm{CoP}_\mathbf{R}$ represent the center of pressure position from the left and right force plates, respectively.

To examine the spatial aspects of postural sway, CoP path length ($\mathrm{CoP}_\mathbf{PL}$) and CoP standard deviation ($\mathrm{CoP}_{\boldsymbol{SD}}$) were calculated. $\mathrm{CoP}_\mathbf{PL}$ (from each foot and the net CoP time series) was calculated by summing the Euclidian distance between successive data points from the anteroposterior (AP) and medial-lateral (ML) CoP time series (Equation 2).

$$\mathrm{CoP_{PL}} = \sum_{i=1}^{n} \sqrt{(\mathrm{CoP_{AP(i+1)}} - \mathrm{CoP_{AP(i)}})^2 + (\mathrm{CoP_{ML(i+1)}} - \mathrm{CoP_{ML(i)}})^2} \quad (2)$$

$\mathrm{CoP}_{\boldsymbol{SD}}$ was calculated by taking the standard deviation of the CoP time series under each foot and the net CoP time series. All standard deviation calculations were made in the AP and ML directions.

Postural TtC and SampEn were calculated to better assess overall postural stability (TtC) and the time-dependent dynamics of the moment-to-moment postural fluctuations (SampEn). TtC was calculated using the methods outlined in Slobounov, Slobounova, and Newell (1997) and Haddad, Gagnon, Hasson, Van Emmerik, and Hamill (2006b). Postural TtC is the time it would take the CoP given its present trajectory to contact the base of support. TtC provides a temporal measure of overall postural stability by assessing the dynamics of the CoP relative to the base of support. A short TtC is indicative of a less stable postural state whereas a long TtC is indicative of a more stable postural state. TtC was only analyzed for the resultant CoP. The measure is not relevant to examine under each foot because there are no balance consequences to the CoP of one foot reaching the base of support.

SampEn was used to determine the time-dependent dynamics of the CoP under each foot. SampEn provides information about the complexity of the CoP fluctuations because it examines how the system evolves over time (Rhea et al., 2011). SampEn was calculated from the net CoP time series and the CoP time series from the right and left foot using the algorithms by Richman and Moorman (2000) that are downloadable from http://www.physionet.org (an online Web site that provides software to analyze complex biological signals). Before calculating SampEn, the embedding dimension and radius were set to 2 and 0.2, respectively. These input parameters have been found to be appropriate for unfiltered CoP data (Ramani, Seigle, Lagarde, Bouchara, & Bernard, 2009).

Before calculating CoP_{PL}, CoP_{SD}, and TtC, data were filtered at 6Hz using a fourth-order low-pass Butterworth filter. SampEn was calculated using unfiltered data because filtering may impose nonbiological deterministic characteristics to the CoP time series (Haddad et al., 2008).

Results

Hypothesis 1: Between-Limb Differences During Unloaded Self-Selected Stance

To test the hypothesis that there are differences between the limbs in the spatial and time-dependent characteristics of the CoP during unloaded self-selected stance, a paired sample *t* test was conducted on percentage of weight distribution, CoP_{PL}, AP CoP_{SD}, ML CoP_{SD}, AP SampEn, and ML SampEn with foot (left vs. right) as the within-subject term. Additionally, a binomial distribution was used to examine if there was a tendency (above chance levels) for right-handed individuals to place more weight on their right limb. There was a significant difference in weight bearing during unloaded self-selected stance, $t(21) = 2.763$, $p = .012$. Subjects tended to load 48.6% of their body weight on their left limb and 51.4% of their body weight on their right limb. Note that not all subjects demonstrated similar loading: 16 of the 22 subjects placed a greater load on their right limb. Using a binomial distribution, set to a .05 threshold of significance, it was concluded that right-handed individuals significantly loaded the right limb to a greater degree than the left limb. Despite laterality differences in weight distribution, no significant differences were observed between the right and left limbs in any of the other spatial or time-dependent variables examined. CoP_{SD} in the AP direction was 3.5 mm and 3.4 mm in the left and right limbs, respectively, $t(21) = 0.225$, $p = .824$. CoP_{SD} in the ML direction was 0.9 mm in the left and right limbs, $t(21) = 0.195$, $p = .847$. SampEn in the AP direction was 0.269 and 0.288 in the left and right limbs, respectively, $t(21) = 0.801$, $p = .432$. SampEn in the ML direction was 0.868 and 0.833 in the left and right limbs, respectively, $t(21) = 0.674$, $p = .508$. Finally, CoP_{PL} was 112 mm and 105 mm in the left and right limbs, respectively, $t(21) = 0.702$, $p = .491$. Hypothesis 1 was therefore only supported in the weight distribution variable.

Hypothesis 2: Postural Asymmetries When Holding an Evenly Distributed Load in Both Hands

To test the hypothesis that between-limb asymmetries would increase as the weight of an evenly distributed load increased during self-selected stance, a two-way analysis of variance (ANOVA) was run on CoP_{PL} (Figure 1A), ML

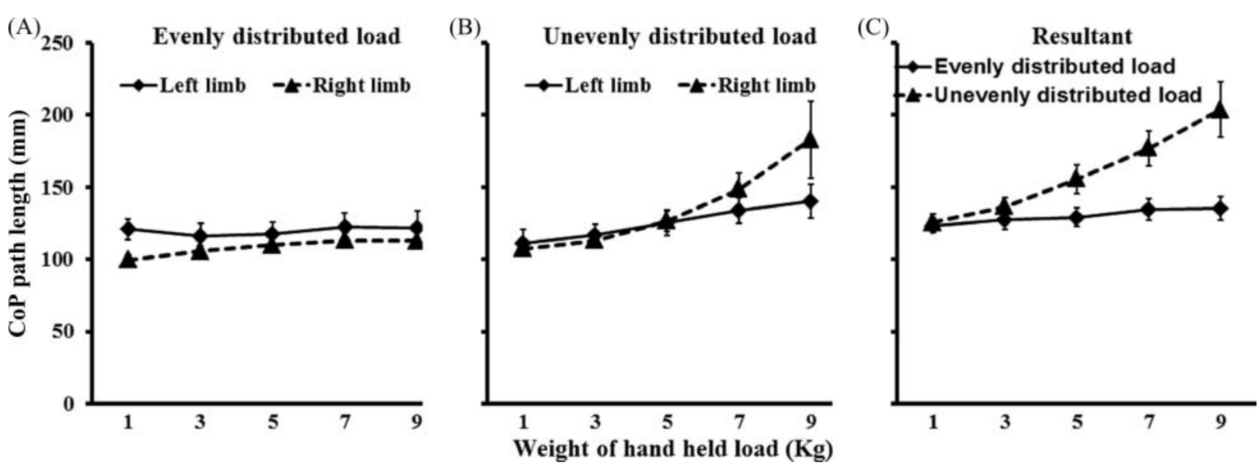

FIGURE 1. The center of pressure (CoP) path length for the right and left limbs when (**A**) an evenly distributed load was held in both hands and (**B**) the load was held only in the left hand, and (**C**) the resultant CoP path length in the evenly distributed and unevenly distributed load conditions.

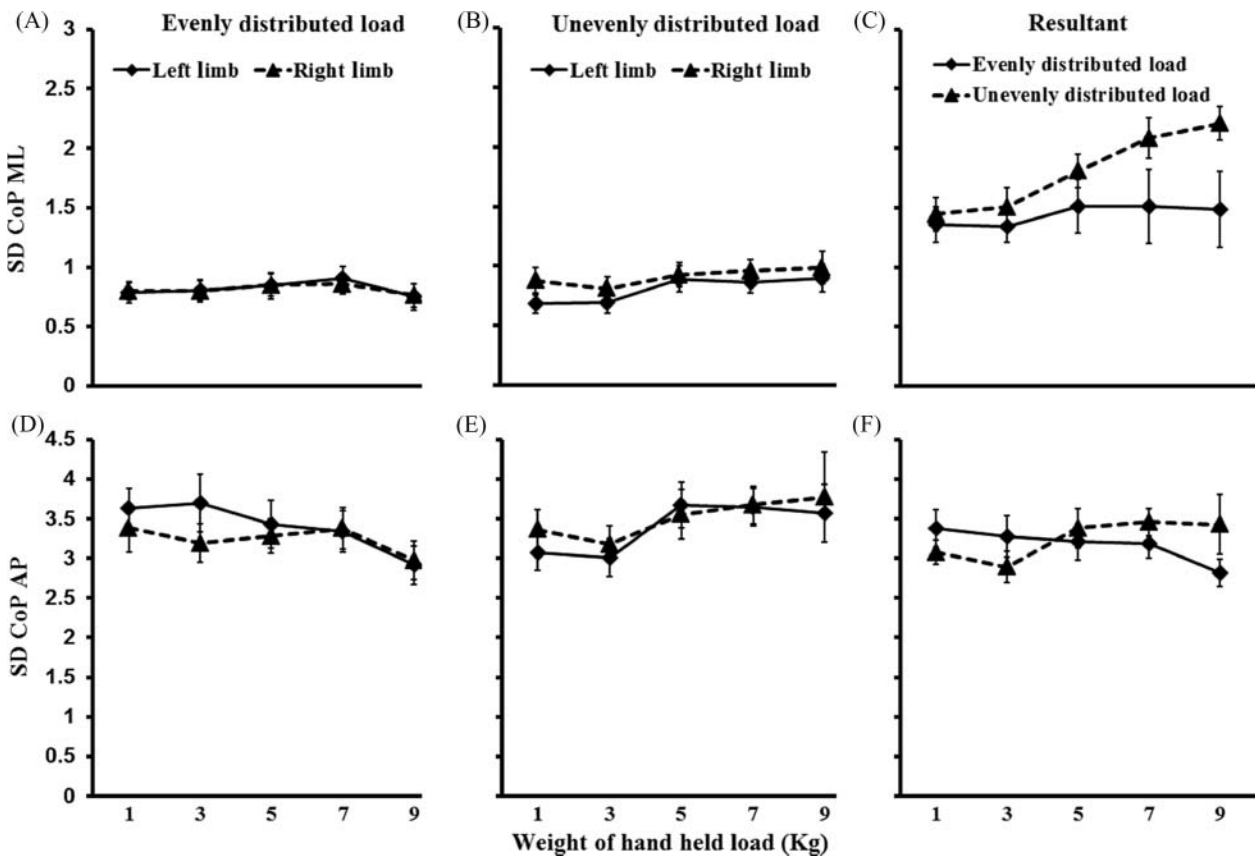

FIGURE 2. Center of pressure standard deviation (CoP_{SD}) in the medial-lateral (**A**–**C**) and anteroposterior (**D**–**F**) directions as a function of load magnitude (*x*-axis). CoP_{SD} under each limb (left limb, solid line; right limb, dashed line) for the evenly distributed (**A** and **D**) and the unevenly distributed load conditions (**B** and **E**). The resultant CoP_{SD} is shown (**C** and **F**) for evenly distributed (solid line) and unevenly distributed loads (dashed line).

CoP_{SD} (Figure 2A), AP CoP_{SD} (Figure 2D), ML SampEn (Figure 3A), and AP SampEn (Figure 3D) in the evenly distributed load trials with side (left vs. right) and weight (no load, 1, 3, 5, 9 kg) as the within-subject terms. Any significant Weight × Side interactions were considered to be indicative of the manifestations of functional asymmetries. No Weight × Side interactions were observed in CoP_{PL} $F(5, 105) = 1.67$, $p = .147$ (Z)ML CoP_{SD} ($F(5, 105) = .202$; $p = .961$; Figure 2A); AP CoP_{SD} ($F(5, 105) = 1.77$; $p = .125$; Figure 2D); ML SampEn ($F(5, 105) = .885$; $p = .494$; Figure 3A) or AP SampEn ($F(5, 105) = 1.30$; $p = .268$; Figure 3D), (Figure 1A). There were also no main effects of weight or side observed in any of the aforementioned variables ($p > .05$).

In addition to the CoP characteristics under each foot, changes in weight distribution were also examined. There were no changes in how subjects distributed their weight as the magnitude of the evenly distributed load increased ($p > .05$; Figure 4). Similar to the no-load trials, subjects loaded 48.4% of their total body weight on the left limb for all magnitudes of the evenly distributed load. The subjects' total body weight included their body weight plus the weight of the held loads. Hypothesis 2 was therefore not supported. The lack of an effect between loaded and unloaded conditions also mitigated any concerns regarding changes in arm position (greater shoulder abduction for loaded conditions) affecting behavior.

Hypothesis 3: Postural Adaptations When Holding an Unevenly Distributed Load

To test the hypothesis that the right and left limbs would demonstrate different adaptations as the weight of an evenly distributed load increases during self-selected stance, the same statistical tests were performed as in Hypothesis 2 with the exception that (a) the analyses were performed in the unevenly loaded trials and (b) the unloaded trials were not included in the statistical model. For CoP_{PL} a significant Load × Side interaction was observed ($F(4, 48) = 4.729$, $p = .002$; Figure 1B). A Tukey post hoc analysis revealed that CoP_{PL} was significantly greater at the 9 kg load in the unloaded limb compared to the loaded limb. No significant main effects or interactions were

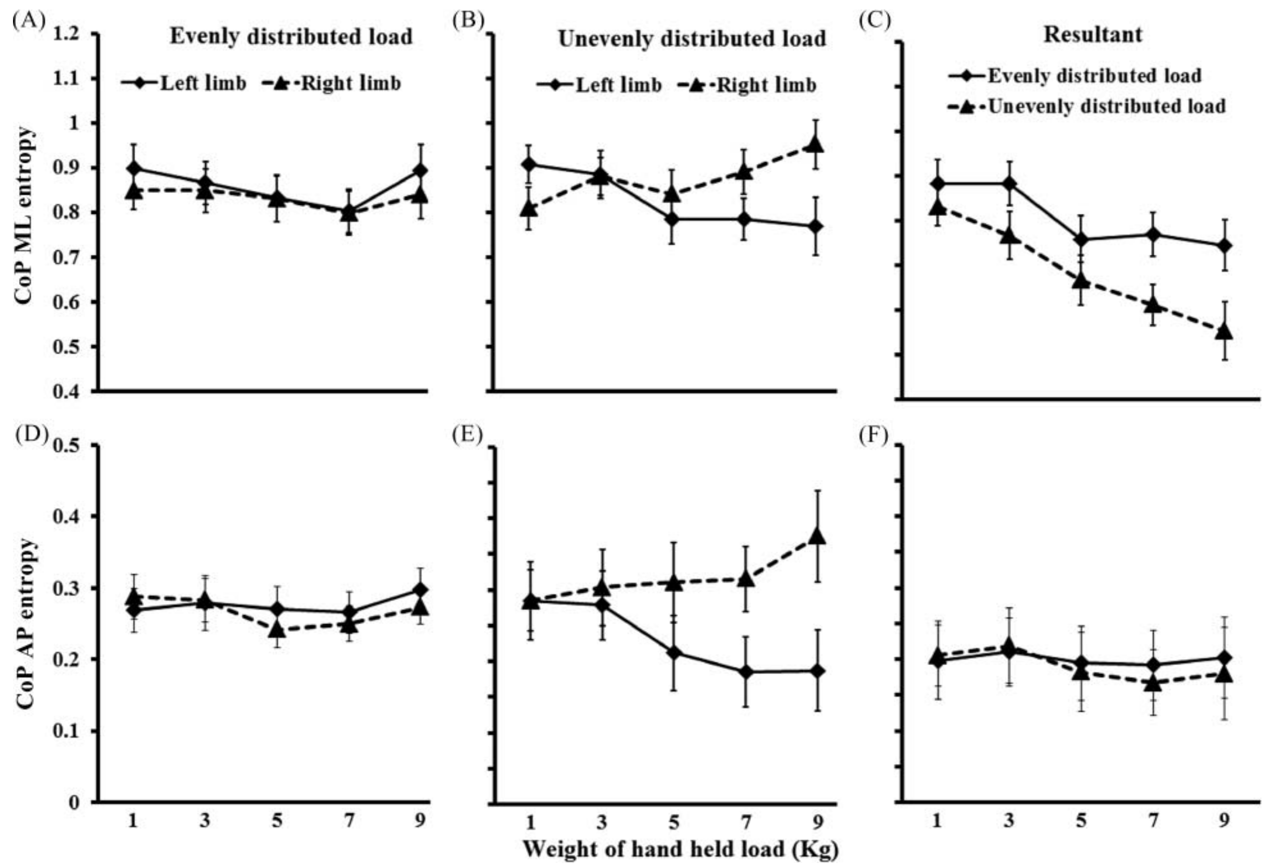

FIGURE 3. Center of pressure (CoP) sample entropy in the medial-lateral (**A**–**C**) and anteroposterior (**D**–**F**) directions as a function of load magnitude (*x*-axis). CoP sample entropy under each limb (left limb, solid line; right limb, dashed line) for the evenly distributed (**A** and **D**) and the unevenly distributed load conditions (**B** and **E**). The resultant CoP sample entropy is shown (**C** and **F**) for evenly distributed (solid line) and unevenly distributed loads (dashed line).

observed in CoP_{SD} in either the ML (Figure 2B) or AP (Figure 2E) direction ($p > .05$).

There were significant Weight × Side interactions in SampEn in the ML, $F(4, 84) = 9.15$, $p < .0001$ (Figure 3B), and AP, $F(4, 84) = 9.63$, $p < .0001$ (Figure 3D) directions. As the magnitude of the load increased, SampEn decreased in the left (loaded) leg and increased in the right (unloaded leg) leg in the AP and ML directions. A Tukey post hoc analysis revealed that AP entropy was not different between the right and left limbs at the 1 and 3 kg loads but was different at the 5, 7, and 9 kg loads. Only the 9 kg load was different for ML entropy.

In addition to the CoP characteristics under each foot, changes in weight distribution were also examined. As the magnitude of the unevenly distributed load increased, subjects could have shifted their body weight more to the unloaded side to distribute the load more evenly. Instead, a greater weighting was observed on the loaded limb ($p < .05$; Figure 4). A Tukey post hoc analysis revealed that all loads were significantly different from each other. Hypothesis 3 was therefore supported. Specifically, the right and left limbs demonstrated different adaptations to the unevenly distributed load.

Time to Contact

Although not used to specifically test any of the hypotheses, postural TtC was calculated to confirm that the tasks were increasingly challenging to the postural system. TtC from the net CoP was used to measure the degree of instability that resulted from holding the load in the evenly and unevenly distributed load conditions (Figure 5). A two-factor ANOVA was used, with load distribution (even and uneven) and weight (1, 3, 5, 7 and 9 kg) as the two factors. There were significant main effects of load distribution, $F(1, 21) = 45.000$, $p < .001$, and weight, $F(4, 84) = 33.967$, $p < .001$, for TtC. Specifically, TtC was shorter during unevenly distributed load conditions ($M = 3.20$ s, $SD = 0.42$) compared to evenly distributed load conditions ($M = 3.52$ s, $SD = 0.54$). In addition, a significant Load Distribution × Load Magnitude interaction was observed, $F(4, 84) = 18.983$, $p < .001$. TtC did not significantly change as load increased during the

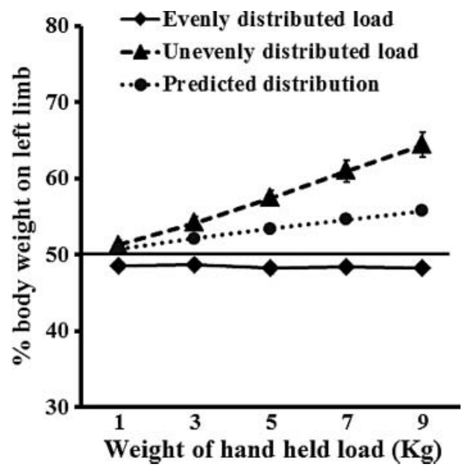

FIGURE 4. Percentage of total body weight supported on the left limb in the evenly distributed and unevenly distributed load conditions. The total body weight includes the subject's body weight plus the weight of the held load. The predicted distribution line is the percentage weight distribution on the left limb that would have been predicted based solely on the added weight of the hand load.

evenly distributed conditions. However, during unevenly distributed conditions, TtC decreased as load increased. Post hoc analyses revealed that TtC in the 1 and 3 kg load conditions was significantly longer than the 5, 7, and 9 kg conditions; TtC in the 5 kg condition was significantly longer than the 7 and 9 kg conditions; and TtC in the 7 kg condition was significantly longer than 9 kg condition when unevenly distributed loads were held.

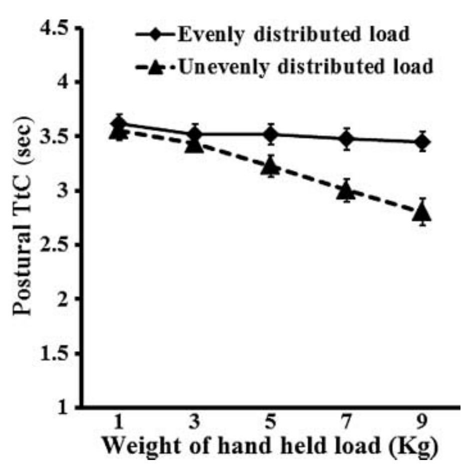

FIGURE 5. The time to contact (TtC) in the evenly distributed and unevenly distributed load conditions.

Resultant CoP

To determine if the CoP data collected from two force plates provided information that cannot be obtained from only one force plate, differences in all CoP variables were examined using only the resultant CoP trajectory. A two-way ANOVA was performed on the resultant CoP with weight magnitude and load distribution as the within-subject factors. There was a significant Load Distribution × Load Magnitude interaction, $F(4, 84) = 9.956, p < .01$, on the resultant CoP_{PL}. In addition, significant main effects of load distribution, $F(1, 21) = 16.829$, $p < .0001$, and load magnitude, $F(4, 84) = 18.984$, $p < .0001$, were observed (Figure 1C). Post hoc analyses revealed that the resultant CoP_{PL} in the 1 and 3 kg unevenly distributed load conditions were significantly shorter than the 5, 7, and 9 kg conditions. No differences in CoP_{PL} were observed as a function of load magnitude in the evenly distributed load conditions.

There was a significant Load Magnitude × Load Distribution interaction, $F(4, 84) = 3.053$, $p = .021$, in the resultant ML CoP_{SD} (Figure 2C). Post hoc analyses revealed that there were no ML CoP_{SD} differences as load magnitude increased in the evenly distributed load conditions. In the unevenly distributed load conditions, ML CoP_{SD} was significantly shorter in the 1 kg condition compared with the 9 kg condition. Significant main effects of load magnitude, $F(4, 84) = 6.634$, $p < .0001$, and load distribution, $F(1, 21) = 6.945$, $p < .05$, were also observed (Figure 2C). There was no significant Load Magnitude × Load Distribution interaction, $F(4, 84) = 2.727$, $p = .035$, in the resultant AP CoP_{SD}. The evenly and unevenly distributed conditions were significantly different at the 9 kg load level (Figure 2C). Additionally, no main effects of weight, $F(4, 84) = 0.620$, $p = .64$, or load distribution, $F(1, 21) = 0.275$, $p = .605$, were observed (Figure 2F).

There was no significant Load Magnitude × Load Distribution interaction, $F(4, 84) = 1.801, p = .194$, in the resultant ML SampEn. However, main effects of load magnitude, $F(4, 84) = 17.711$, $p < .0001$, and load distribution, $F(1, 21) = 17.445$, $p < .0001$, were observed (Figure 3C). In general, the resultant ML SampEn tended to decrease with increasing load magnitude in the evenly and unevenly distributed load conditions (Figure 3C). There was no significant Load Magnitude × Load Distribution interaction, $F(4, 84) = 1.095$, $p = .307$, in the resultant AP SampEn. In addition, no main effects of weight magnitude, $F(4, 84) = 2.317$, $p = .06$, or load distribution, $F(1, 21) = 1.209$, $p = .284$, were observed in resultant AP SampEn (Figure 3F).

Discussion

In the present study we examined postural adaptations and functional postural asymmetries that occur in healthy young adults as they stood and held either an evenly or unevenly distributed load of varying magnitude. Functional asymmetries were defined as CoP differences between the right and left limbs that occurred as an evenly distributed load was held.

The trials where a load was held in only one hand were used to examine postural adaptations that resulted from holding a unilateral load. In addition, we examined the degree to which postural asymmetries are present in young healthy individuals during unperturbed stance (when no load was held).

Postural Asymmetries During Quiet Stance

Regarding the first hypothesis, weight-bearing asymmetries were present during unloaded stance. Similar to what has been observed in a previous study (Blaszczyk et al., 2000), subjects supported 51.4% of the body weight on their right (dominant upper limb) side and 48.6% of their body weight on their left side. Interestingly however, results from the present study show that during unloaded stance there is no difference in the spatial or temporal CoP characteristics between the right and left feet. Therefore, the issue of whether young adults stand asymmetrically is less straightforward. Whereas weight bearing does tend to be slightly asymmetrical, both limbs appeared to have similar CoP characteristics during unloaded quiet standing.

Blaszczyk et al. (2000) suggested that asymmetry in weight distribution is functional because it allows subjects to prepare a preferred leg to make a step should it become necessary due to an unexpected perturbation. This interpretation is consistent with the gait initiation literature, which has found individuals initially load the foot they plan to take the first step with (Jian, Winter, Ishac, & Gilchrist, 1993). However, if weight-bearing asymmetries were functional, differences in CoP movement under the anticipated swing limb versus the anticipated stance limb would have been predicted. For example, an anticipated lateral CoP movement of the loaded limb would result in an increased CoP_{PL} under that limb. Because none of the CoP parameters between the right and left limbs were different, the present results do not support the theory that asymmetries in quiet unladen stance are functional.

Postural Asymmetries When Holding Evenly Distributed Loads in Each Hand

Regarding the second hypothesis, we thought that as the magnitude of an evenly distributed load increased, posture would become more asymmetrical. Therefore, as the task became more difficult, each limb would perform a more specialized role in maintaining upright stance. For example, similar to gait, one limb would be used for propulsion (or driving the CoP) whereas the other limb was used more for stabilization (Sadeghi et al., 2000). There was no evidence to support this, as no side by weight interactions were found in any of the CoP variables examined. Additionally, there were no changes in weight bearing as the magnitude of the evenly distributed load increased. As discussed previously, if asymmetric weight bearing was indeed functional, a growing asymmetry would have been expected as the magnitude of the load increased. The finding that functional asymmetries were not found in posture was surprising given that asymmetries have been found to be functional in gait and manual control (Guiard, 1987; Haddad, Van Emmerik, Whittlesey, & Hamill, 2006). Additionally, as discussed previously, previous research (and the present study) has shown that even young adults stand with some degree of asymmetry during quiet stance (Blaszczyk et al., 2000; Hesse et al., 1996). The fact that young adults stand with some degree of asymmetry, when presumably they are capable of standing symmetrically, also assumes that the observed asymmetry is functional in some way (Hesse et al.). However, it should be noted that the weighting asymmetries found in the present study and the studies by Blaszczyk et al. and Hesse et al. were typically less than 5%. It is unknown if such a small difference is functional.

There are several possible reasons why functional asymmetries were not found in the present study. First, it is possible that holding an evenly distributed load while standing is a relatively less difficult and complex task than gait or fine manual control, therefore negating the need for each limb to take on a specialized role of completing the goal-directed task. The TtC data from the evenly loaded trials supports this interpretation. Specifically, there were no differences in TtC across any of the evenly distributed load trials (Figure 5). The invariance in TtC suggests that postural stability did not decrease as the magnitude of the evenly distributed load increased. Additionally, none of the CoP characteristics between the right and left foot were different as the load magnitude increased, suggesting that an increased load in the evenly distributed condition might not have made the task more difficult. If a more difficult postural task (such as standing in a dark room or on a compliant surface) had been employed, perhaps functional asymmetries would have been observed. Second, it is possible that young healthy adults did not need to exhibit functional asymmetries to safely and effectively complete the task. Functional asymmetries may have been observed if the same methodology was applied to an older or impaired population. Finally, although a variety of spatiotemporal measures were examined, it is also possible that there are measures that exhibit functional asymmetry, but they were not calculated in the present study. For example, variables such as muscle stiffness or muscle contraction may have demonstrated functional asymmetries. Although the gait and manual control research has found differences in left versus right limbs, this categorization may not be appropriate for quiet stance. Perhaps the existence of limb load asymmetry should provide a basis for categorizing subjects; this is explored more fully in the next section.

Postural Asymmetries When Subjects Are Categorized Based on Limb Load Preference

Although the overall conclusion from the data discussed previously is that asymmetries in stance are not functional, it is important to note that all analyses compared the left versus right limb of right-handed subjects. In this analysis we assume that there is an anatomical or neurophysiological reason the left lower limb is different from the right lower limb for right upper limb–dominant subjects. However, this assumption may be incorrect. For example, past research has suggested that foot preference is dependent in part on the context of a concurrently performed task (Balasubramaniam & Turvey, 2000; Hart & Gabbard, 1997). Thus, it may be best to assess lower limb dominance using more task specific functional measures. For example, Balasubramaniam and Turvey found that postural movements become lateralized when subjects performed a standing task that required an attentional shift to one side of the body. This finding has strong implications for this study and past research on postural asymmetries because it suggests that lower limb or foot dominance can only be reliably assessed using task-specific measures. Thus, to further examine the role of functional postural asymmetries during quiet stance, subjects were categorized as a function of preferred limb weighting. Sixteen of the 22 right-handed subjects tended to place a greater magnitude of body weight on their right limb while quietly standing with no added load. Thus, we reran the same statistical analyses used to address Hypothesis 1 with the exception that the subjects who preferred to place a larger magnitude of body weight on their left limb or did not show a strong preference were removed from the subject pool. When compared in this manner, $CoP_{\mathbf{PL}}$ was significantly greater (20%) in the right limb (limb supporting more body weight) during unladen quiet stance. As previously mentioned, a longer $CoP_{\mathbf{PL}}$ may reflect an anticipated lateral CoP movement of the loaded limb in preparation for making a step to recover from a perturbation.

In the conditions where an evenly distributed load was held, only 13 of the 22 subjects demonstrated a preference for the right foot in all conditions examined (0, 1, 3, 5, 7, and 9 kg conditions). The statistical analyses used to address Hypothesis 2 were therefore rerun on these 13 subjects. No Side × Load Magnitude interactions were found. However, main effects were observed, where path length and CoP_{SD} in the AP direction were longer in the right limb (limb supporting more body weight) compared with the left limb. These findings were similar to those discussed previously in the unloaded condition. Taken together, the results from this reanalysis provide some support that functional asymmetries in stance are present and observable if subjects are categorized based on the limb they chose to load and not on upper limb preference or dominance. However, there would have been greater support for functional postural asymmetries in stance if Side × Load Magnitude interactions were found in this reanalysis. These interactions would have suggested that asymmetry increased as a mechanism to compensate for the greater task demands of holding a heavier load. However, because none of the CoP characteristics changed with increasing load in the evenly distributed load condition, there is no evidence that difficulty increased with increasing load. To fully explore if postural asymmetries are functional, future researchers should adopt a paradigm where the increasing difficulty of the task is confirmed (e.g., standing on a compliant surface or with limited vision).

Additionally, results from this reanalysis support the idea that lower limb dominance should be assessed using task specific measures (e.g., which leg supports more weight when carrying a load). It is important for future researchers to examine if there are more appropriate ways (other than the leg that supports a larger percentage of body mass) to categorize limb dominance and functional asymmetries while carrying a load. For example, anthropometrical differences between the right and left side of the body could potentially be a factor that explains the small differences in weight distribution found in the current study and in past research.

Postural Asymmetries When Holding an Asymmetrical Load in the Nondominant Hand

The third purpose of this study was to examine postural adaptations that occurred as individuals held a unilateral load in their nondominant hand. As the magnitude of the load increased, percentage of weight bearing on the ipsilateral side of the load also increased. Therefore, subjects did not shift their weight to counter an externally imposed load. Rather, subjects shifted their weight in the direction of the applied load, as the percentage of body weight that was shifted to the loaded limb was greater than would have been predicted solely by the weight of the held load (Figure 4). This finding is interesting given that the load shifted the location of the CoP closer to the boundary of the base of support resulting in decreased postural stability. Exactly why individuals shifted their body weight toward the load is unknown. It is possible that, as suggested by Blaszczyk et al. (2000), the increased asymmetry (unloading of one limb) allowed the subject to prepare for taking a step should the need arise to offset a threat to balance. Additionally, it is possible that the unilateral load resulted in an attentional shift to the loaded limb. This finding is consistent with Balasubramaniam and Turvey (2000), who found that postural control became lateralized when subjects performed a suprapostural task that required an attentional shift to one side of the body.

In the unevenly distributed load conditions, TtC decreased as the magnitude of the held load increased (Figure 5). Therefore, in agreement with the clinical literature, it appears that imposed asymmetries can lead to postural instabilities (Asseldonk et al., 2006; Cheng, Wu, Liaw, Wong, & Tang, 2001; Genthon & Rougier, 2005). Interestingly, TtC did not begin to decrease until the subjects held the 5 kg load, suggesting that some degree of asymmetry can be tolerated in young adults before they become less stable. The ability of young adults to tolerate this level of instability may also explain why they tended to shift their weight toward the side of the load. It is also possible that the instructions given to the subject not to rest the bucket on their leg resulted in a body position that was shifted towards the loaded limb.

Interesting results also emerged with respect to CoP changes under each foot that occurred as the unevenly distributed load increased. CoP_{PL} did not change with increasing load on the ipsilateral side of the load (Figure 1A), but increased on the contralateral side (Figure 1B). This suggests postural fluctuations were minimized or maintained on the ipsilateral side of the load, but greater CoP movement was allowed on the contralateral side. This interpretation is in line with the CoP SampEn data. In the AP and ML directions, a significant interaction between leg and load was observed for SampEn (Figure 3). Specifically, as the unevenly distributed load increased, SampEn decreased under the loaded foot but increased under the unloaded foot. Thus, the CoP movements under the loaded foot became more regular and CoP movements under the unloaded foot became less regular or more complex with increasing load. The typical interpretation of a decrease in CoP entropy is that fewer functional degrees of freedom are being recruited; which limits the stability and adaptability of the postural system but simplifies control (Donker, Roerdink, Greven, & Beek, 2007; Haddad et al., 2008). The decreased complexity may be a consequence of increased muscle stiffness, such as seen with threat (Azevedo et al., 2005; Carpenter, Frank, Silcher, & Peysar, 2001), or during the performance of a secondary task (Dault & Frank 2004). Greater regularity of the CoP has also been observed in individuals with a variety of neurological disorders, including cerebral palsy (Donker, Lebdt, Roerdink, Savelsbergh, & Beek, 2008), concussions (Cavanaugh et al., 2006), and Parkinson's disease (Vaillancourt & Newell, 2000). However, to our knowledge CoP entropy under the right and left feet has not been examined. Interestingly, the increase in entropy under the unloaded limb suggests the nervous system compensated for the loss of flexibility under the loaded limb. That is, a tradeoff was observed between controllability and flexibility of the loaded and unloaded limbs. For example, in the present study, we suggested that entropy in the loaded leg decreased due to a freezing of the limb's degrees of freedom. Although this would decrease the ability of that leg to adapt to varying environmental or task constraints, it would make control easier. The ipsilateral loss in entropy was apparently compensated with a contralateral increase in entropy. These results may be important for understanding how individuals complete typical load carriage tasks. Unlike the young adults in the present study, older individuals may not exhibit decreased flexibility in the loaded limb coupled with increased flexibility in the unloaded limb, possibly contributing to an increased risk of suffering a fall.

Resultant CoP Versus the CoP Under Each Foot

We used two force plates to systematically examine the role of the left and right limbs in maintaining bipedal stance. The findings indicate that important information regarding the dynamics of postural control can only be determined with two force plates. For example, as unilateral load increased, entropy decreased in the loaded leg but increased in the unloaded leg. Interestingly however, there were no entropy differences at any load magnitude when examining the resultant CoP. Differences between the resultant and individual force plate CoP data were not as pronounced in the evenly distributed load conditions. This data suggests that when examining postural adaptations to imposed asymmetries (such as the adaptations that occur in stroke patients) it is important to use two force plates.

In summary, there were three main conclusions from this study. First, there was no conclusive evidence that in unladen quiet stance or when holding evenly distributed loads, postural asymmetries across the right and left limbs were functional. If asymmetries were functional (similar to what is observed in the gait or manual control literatures) an increased asymmetry would have been expected as the magnitude of the load increased. However, when subjects were categorized as a function of preferred limb weighting when holding no load or holding evenly distributed load, there was some evidence that stance asymmetries are functional. Thus, assessing lower limb dominance using a preferred-loading criteria may be necessary to capture functional stance asymmetries. Second, when holding a load in only one hand, the CoP dynamics of the right and left feet differentially changed. Specifically, the loaded limb CoP displacement became less complex, while the unloaded limb increased CoP displacement coupled with increased complexity. These results suggest that the more regular (less adaptable) dynamics adopted by the limb supporting the added load were compensated for by the unloaded limb. Third, using two force plates to examine the CoP under each foot captures postural adaptations that are not observable when examining only the net CoP.

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