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A test of the functional asymmetry hypothesis in walking

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Abstract

The causes of bilateral asymmetries during able-bodied gait are unclear. These asymmetries may represent a form of *functional asymmetry*, which has been defined as a consistent task discrepancy between the two lower limbs. According to this theory, the non-dominant lower limb contributes more to support, while the dominant lower limb contributes more to forward propulsion. Impulses due to vertical and propulsive (anterior) ground reaction forces during gait are directly associated with center of mass support and forward propulsion, respectively, but have not yet been investigated in the context of functional asymmetry. The purpose of this study was to compare bilateral ground reaction force impulses to evaluate functional asymmetry as an explanation for gait asymmetries. We hypothesized that if gait asymmetries are functional in nature: (1) vertical impulse (support) would be greater for the non-dominant limb, (2) propulsive impulse would be greater for the dominant limb, and (3) increasing walking speed would cause disproportionate increases in dominant-limb propulsive impulse, relative to the non-dominant limb propulsive impulse. Asymmetry for vertical and propulsive impulses was quantified during slow, preferred, and fast walking in 20 healthy adults. No significant bilateral differences existed between sample means for vertical or propulsive impulses at the slow or preferred speeds, yet dominant-limb propulsive impulse was 7% greater than non-dominant limb propulsive impulse at the fast speed. In conclusion, impulses were generally symmetrical, offering little support for the functional asymmetry idea, except at the fast speed, where contributions to propulsion were greater for the dominant limb.

Keywords: Able-bodied gait; Bilateral asymmetry; Impulse

1. Introduction

Furthering our understanding of human able-bodied gait is an important step towards developing enhanced rehabilitation protocols for pathological gait. Although the kinematics and kinetics of human walking have been described extensively, many aspects of gait are still not well understood. Bilateral asymmetry, defined as a lack of perfect agreement between the lower limbs [1], has been observed during able-bodied gait in kinematic [2], kinetic [1,3], and electromyography [4] data. However, underlying causes of these asymmetries remain unclear. Some investigators have suggested that these bilateral differences represent a form of *functional asymmetry*, defined as a consistent task discrepancy between non-dominant and dominant lower limbs [5]. According to this theory, the non-dominant lower limb contributes more to support (upward acceleration of the center of mass), while the dominant limb contributes more to propulsion (forward acceleration of the center of mass) during walking [5].

The presence of upper-limb functional asymmetries is obvious (i.e., handedness), and functional asymmetries have been documented in the context of lower-limb tasks other than walking [6,7]. These tasks include kicking a ball, stepping up on a chair, picking up pebbles with the toes, and tapping out the rhythm to a melody. In these activities, the non-dominant limb is generally used to support body weight, while the dominant limb provides propulsion or performs

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dexterous tasks. It is a logical extension that these inherent neuromuscular asymmetries may also express themselves during able-bodied gait. In a recent review of the literature, evidence was presented in support of the functional asymmetry concept, as an explanation for bilateral asymmetries in able-bodied gait [5]. However, a close examination of several of the cited studies suggests that this conclusion may be premature. For example, some studies that have been cited in support of functional asymmetry in able-bodied gait did not involve walking [8–10]. Moreover, data in an oft-cited study [11] contradict an apparent typographical error in the abstract, giving the false impression that the results support the concept of functional asymmetry. Aside from these issues, one of the most striking aspects of the existing literature regarding functional asymmetry is that impulses due to the vertical (support) and anterior–posterior (propulsion) components of the ground reaction force (GRF) have not been considered. These variables are especially relevant because, unlike many other variables, they are unambiguously linked to the way in which each limb contributes to support and forward propulsion of the whole body center of mass during gait.

Given this apparent gap in the literature, the purpose of this study was to investigate bilateral asymmetries in impulses due to vertical and anterior–posterior GRFs during able-bodied gait. If bilateral differences exist and represent functional asymmetries, then we predict that the following two hypotheses should be supported: (1) support impulse, due to the vertical GRF, will be greater for the non-dominant limb, relative to the dominant limb, and (2) propulsive impulse, due to the anterior–posterior GRF, will be greater for the dominant limb, relative to the non-dominant limb. In an attempt to further test the concept of functional asymmetry, a speed manipulation was used to evaluate a third hypothesis: (3) as walking speed increases, propulsive impulse associated with the anterior–posterior GRF will increase more across speeds for the dominant limb, relative to the non-dominant limb. The rationale for this hypothesis, and the lack of a similar prediction for vertical impulse, is that greater walking speeds should require greater propulsive impulse, but not any meaningful change in support impulse due to the independence of gravity on walking speed. The functional asymmetry hypothesis does not make any predictions regarding the influence of gender; however, we collected an equal number of male and female subjects, which allowed us to test for any potential gender effects.

2. Methods

Ten males and 10 females (age = 24 ± 3 years; height = 1.71 ± 0.11 m; mass = 69.6 ± 14.0 kg) who were free from lower-limb injury and any history of neurological disorder participated in this study. Prior to data collection, the project had been approved by the appropriate ethical committee and all subjects gave informed consent. Subject leg length inequality was estimated using the distance between the greater trochanter and lateral malleolus [12], measured via reflective markers with the subject in a static, standing posture. Mean leg-length inequality was 1.4 ± 1.1 cm, which is of a small enough magnitude that it is not expected to be associated with gait asymmetry [13]. The dominant limb was identified as the limb used to kick a ball [14]. For each subject, the preferred walking speed was determined from the mean speed of five initial walking trials. Immediate feedback on walking speed consistency was provided to subjects using an opto-electronic timing device (Lafayette Instrument Co., Lafayette, IN, USA), and actual walking speeds were determined after data collection from the tracked motion of a reflective marker placed on the sacrum (60 Hz, Motion Analysis Corp., Santa Rosa, CA, USA). The mean preferred speed for the entire sample was 1.49 ± 0.20 m/s, and the slow and fast speeds were set at 20% slower than (1.24 ± 0.15 m/s) and 20% faster than (1.78 ± 0.20 m/s) the preferred speed, respectively. GRF data were collected as subjects walked across two force platforms (1200 Hz; Kistler, Amherst, NY, USA) that were embedded in a 12-m runway. Five satisfactory trials were collected at each speed. Trials were considered satisfactory when: (1) the left foot and the right foot each contacted separate force platforms during consecutive gait cycles, and (2) walking speed was within ±2.5% of the predetermined target speed.

Support impulse was calculated by integrating the vertical GRF over the stance time. Propulsion impulse was determined by integrating the anterior–posterior GRF over the time that the force was oriented in the anterior direction (approximately the second half of stance). Impulses were averaged across the five satisfactory trials for each speed and for each limb, and then normalized to the product of body weight and $\sqrt{\text{limb length}/\text{gravity}}$. This normalization procedure converted impulse into a dimensionless quantity [15]. All data analysis was performed using Matlab (The MathWorks Inc., Natick, MA, USA).

A repeated measures analysis of variance was implemented with SPSS (SPSS Inc., Chicago, IL, USA) using two within-subjects factors: (1) limb (non-dominant and dominant), and (2) walking speed (slow, preferred, and fast). A significant limb × speed interaction was evaluated for each dependent variable. If a significant interaction was not detected, bilateral differences were evaluated for data pooled from all three walking speeds ($p = 0.05$). If a significant limb × speed interaction was detected, *post hoc* comparisons were performed to evaluate bilateral differences at each speed. The potential influence of gender on gait asymmetry was investigated by testing for the existence of a gender × limb × speed interaction for each dependent variable. If a gender × limb × speed interaction was detected, a separate repeated measures analysis of variance was performed for each gender. Nominal *post hoc* significance levels ($p = 0.05$) were adjusted using the false discovery rate procedure [16].

3. Results

Group means for the vertical and anterior–posterior GRFs at the preferred walking speed are presented in Fig. 1. General GRF patterns and magnitudes were similar between limbs at the preferred speed, as well as for the slow and fast speeds (not shown). Means and standard errors for support (vertical) impulse for the entire subject pool are presented in Fig. 2A. No significant limb × speed interaction ($p = 0.089$) existed for support impulse, and no significant bilateral differences existed for data pooled from all three walking

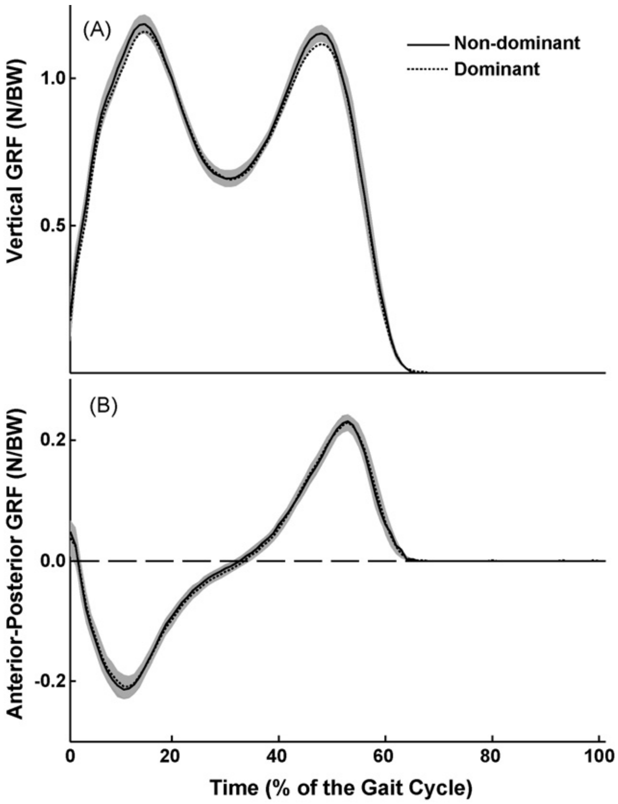

Fig. 1. Preferred-speed means and standard deviations (shaded area) for vertical (A) ground reaction force (GRF) and anterior–posterior (B) ground reaction force, for all subjects. Data have been normalized to body weight (BW) and are expressed as a percentage of the gait cycle. To increase clarity of the figure, only non-dominant limb standard deviations are presented, although dominant limb standard deviations were similar in magnitude and pattern.

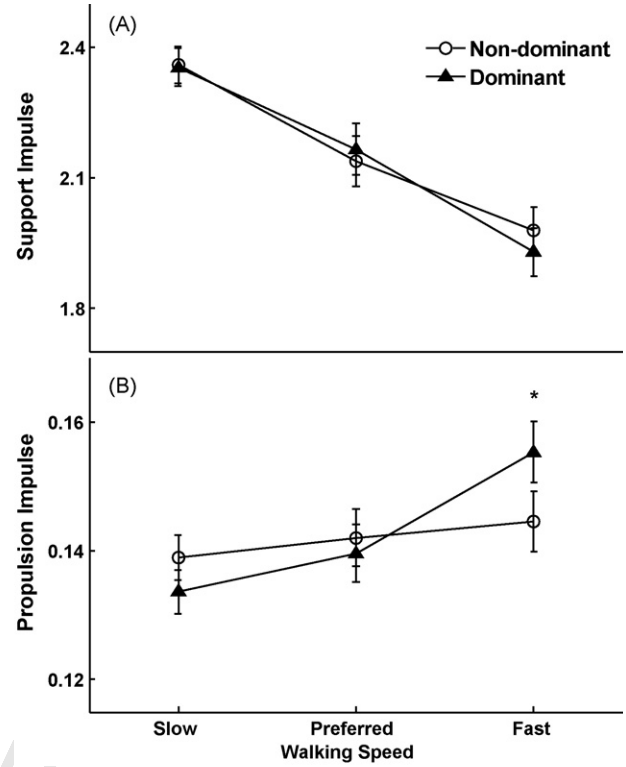

Fig. 2. Means and standard errors for impulses due to vertical (support) and anterior (propulsion) ground reaction force for all subjects ($n = 20$) at each speed. Ordinate values are dimensionless. Support impulse (A) did not differ between limbs at any speed, which contradicted the research hypotheses. Propulsive impulse (B) did not differ between limbs at the slow and preferred speeds, contradicting the research hypotheses. However, dominant-limb propulsive impulse was significantly greater at the fast speed, offering limited support for the idea of functional asymmetry. The asterisk indicates statistical significance.

speeds ($p = 0.187$). Means and standard errors for the propulsive (anterior) impulse for the entire subject pool are presented in Fig. 2B. A significant limb × speed interaction ($p < 0.001$) was detected for propulsive impulse and *post hoc* analyses revealed no significant bilateral differences for slow ($p = 0.208$) or preferred ($p = 0.586$) speeds; however, mean dominant-limb impulse was 7% greater than for the non-dominant limb at the fast speed ($p = 0.013$, ES = 0.53). In summary, support and propulsive impulses were found to be bilaterally symmetrical, except for the propulsive impulse at the fast speed.

A non-significant gender × speed × limb interaction ($p = 0.162$) indicated that gender did not affect gait asymmetry across speeds for the propulsive impulse. However, support impulse asymmetry was different across walking speeds for each gender, as denoted by a significant gender × speed × limb interaction ($p = 0.021$). *Post hoc* comparisons revealed: (1) mean dominant-side support impulse was 4% greater for males at the preferred speed ($p = 0.011$; ES = 0.36; Fig. 3A), but was not different at slow or fast speeds, and (2) mean non-dominant support impulse was 7% greater for females at the fast speed ($p = 0.044$; ES = 0.48; Fig. 3B), but was not different during slow or preferred speeds. However, there was a significant gender × speed × limb interaction ($p = 0.021$) for the support impulse. *Post hoc* analyses indicated that gender effects were limited to a 4% greater dominant limb impulse in males at the preferred speed ($p = 0.011$; ES = 0.36; Fig. 3A) and a 7% greater non-dominant limb impulse in females at the fast speed ($p = 0.044$; ES = 0.48; Fig. 3B).

4. Discussion

One plausible explanation for able-bodied gait asymmetries is that they are a consequence of inherent functional asymmetries in the human neuromuscular system [5]. According to this argument, the non-dominant limb contributes more to support and the dominant limb contributes more to forward propulsion. The existing literature provides some support for these ideas, yet, when considered as a whole, is still inconclusive. Prior to the present study, functional asymmetry had not been evaluated using measures that are directly linked to support (vertical GRF) and propulsion (anterior–posterior GRF) of the whole body center of mass during gait. The purpose of this study

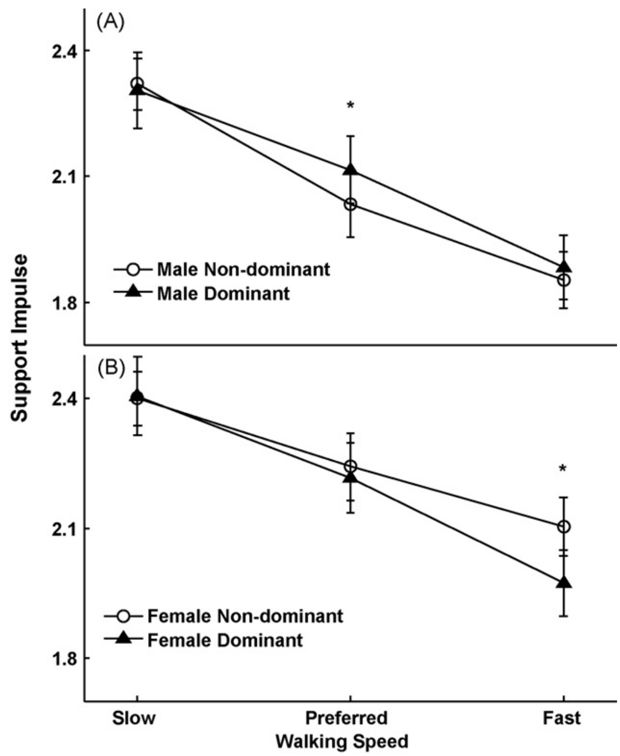

Fig. 3. Means and standard errors for impulse due to vertical ground reaction force (support) for both genders at each speed. Ordinate values are dimensionless. A significant speed × limb × gender interaction indicated that gender affected gait asymmetry differently across speeds. For males ($n = 10$), the mean dominant-limb support impulse (A) was 4% greater at the preferred speed. For females ($n = 10$), the mean non-dominant support impulse (B) was 7% greater at the fast speed. Although the mean difference for female subjects at the fast speed was in the predicted direction, the existence of a significant limb × speed interaction for the support impulse contradicted the research hypotheses, regardless of gender. The asterisks indicate statistical significance.

was to develop and test hypotheses that were formulated to directly evaluate functional asymmetry as an explanation for able-bodied gait asymmetries.

At the preferred speed, which has the greatest ecological relevance, present results failed to support the concept of functional asymmetry in able-bodied gait. Impulse resulting from vertical GRF holistically describes the overall contributions from each limb to support. Therefore, according to the functional asymmetry hypothesis [5], vertical impulse was expected to be greater for the non-dominant limb. However, no significant bilateral difference in vertical impulse was observed when data from both genders were pooled (Fig. 2A). A bilateral difference for support impulse was noted in the male subjects (Fig. 3A), but the effect size was small (i.e., <0.41, [17]), and the difference was in the direction opposite to that predicted by functional asymmetry. Likewise, impulse due to the anterior–posterior GRF holistically describes the overall contributions from each limb to forward propulsion. Consequently, it was expected that propulsive impulse would be greater for the dominant limb [5], yet no significant bilateral difference in propulsive impulse was detected at the preferred speed (Fig. 2B). These results indicate that non-dominant and dominant lower limbs, when considered as whole entities, contribute quite similarly to support and propulsion during preferred-speed walking. This finding is consistent with previous studies that evaluated bilateral GRFs in other contexts [18,19].

When considered together, the existing research considering the concept of functional asymmetry is inconclusive [2,3,8–11,20,21], and conflicting opinions regarding this issue may stem from several different factors. First, variables that are not directly linked to support or propulsion (e.g., medial–lateral GRF) have been used to imply functional asymmetry during gait [20]. Second, asymmetries during movements and tasks that may not be directly relevant to walking (e.g., kicking a ball) have been extrapolated as evidence of functional asymmetry during gait [6,7]. Third, investigators of functional asymmetry during gait have often been misled by a typographical error that contradicts results of a frequently cited study [11]. Fourth, some analyses have excluded variables that are directly involved in support and propulsion. For example, principal component analysis was utilized in one study of functional asymmetry, and ankle joint variables were not identified in the principal components [3]. Consequently, additional bilateral comparisons of ankle joint variables were not considered, excluding a joint that makes substantial contributions to both support and propulsion during gait [22]. This novel application of principal component analysis allowed a unique view of lower-limb function during gait, but the exclusion of a primary contributor to support and propulsion may have limited the relevance to functional asymmetry.

In contrast to the preferred-speed results, the speed manipulation, related to our third hypothesis, yielded limited support for the functional asymmetry concept. Dominant limb propulsive impulse increased more across speeds than non-dominant limb propulsive impulse (Fig. 2B). Furthermore, dominant limb propulsive impulse was significantly greater than non-dominant limb propulsive impulse at the fast speed. The effect size (0.53) for this difference was moderate (i.e., between 0.41 and 0.70), suggesting that the effect was of a meaningful magnitude [17]. Unlike the propulsive impulse, changes in support impulse across speeds for the entire subject pool were similar between limbs (Fig. 2A), which was consistent with our predictions. These results suggest that any inherent neuromuscular asymmetries that may exist in the lower limbs during gait are only evident when propulsive requirements are high. Inclusion of even greater walking speeds might have revealed ever-widening asymmetries, as propulsive requirements were increased. While results for propulsive impulse at the fast speed were consistent with the functional asymmetry hypothesis, the majority of the present findings did not support this viewpoint.

The functional asymmetry hypothesis does not imply any predictions regarding differences in asymmetry between genders, and our results tend to indicate a lack of any systematic gender effect. Gender had no significant effect on

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propulsive impulse, yet, there was a significant gender interaction for support impulse. However, the *post hoc* analysis did not reveal any patterns that were consistent with functional asymmetry for either gender. Dominant limb support impulse was 4% greater for males at the preferred speed (Fig. 3A), which was opposite to our predictions. For females, non-dominant limb support impulse was 7% greater at the fast speed (Fig. 3B), which was in the direction predicted by functional asymmetry. However, the divergence of the dominant and non-dominant limb support impulses across speeds for females was inconsistent with our hypotheses. Overall, gender did not appear to systematically affect gait asymmetry.

The variables considered in the present study exhibited a strong degree of symmetry at the slow and preferred speeds, yet symmetrical GRF impulses do not necessarily imply symmetrical joint kinetics or muscle activations. Regarding the lower limbs during gait, it has been suggested that local asymmetry (asymmetry in joint kinetics and/or muscle activity) may exist, even in the face of global symmetry (symmetrical behavior of the lower limbs as whole entities) [21]. The present results indicate global symmetry, but cannot distinguish local contributions to support and propulsion during gait. In this context, a bilateral investigation of lower-limb joint kinetics and electromyography may uncover functional asymmetries at the joint or muscular level and elucidate an interesting paradox (global symmetry and local asymmetry) which has thus far been explained as a possible compensation mechanism [21].

In summary, this study yielded two major findings. First, there was no evidence of functional asymmetry during preferred-speed walking. Specifically, there was no tendency for the non-dominant limb to contribute preferentially to support, or the dominant limb to contribute preferentially to propulsion. Second, there was limited support for functional asymmetry at the fast walking speed, as the dominant limb contributed more to propulsion than the non-dominant limb, when the demands were high. Additionally, the effects of gender were also analyzed and, while there were some isolated gender effects, these did not tend to be consistent with functional asymmetry. Overall, the global function of the limbs, with regards to support and propulsion, was found to be quite symmetrical, particularly at low to moderate walking speeds.

Q1 Conflict of interest

Authors do not have any financial or personal relationships with other people or organizations that would have inappropriately influenced the results and conclusions of this study.

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