

Original Article

Detection of bilateral asymmetries in the lower extremities under various loading conditions in healthy subjects: an experimental study.

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Abstract

The purpose of the study was to detect bilateral asymmetry in the lower extremities by investigating the kinetics and kinematics of the stride in normal gait under various loading conditions. It was hypothesised that the vertical components of the ground reaction forces and the vertical impulse would be larger in the non-dominant limb during the first distinctive phase of the stride whilst the dominant limb was expected to present larger anterior-posterior ground reaction forces and propulsive impulse during the second phase. The center of mass was expected to travel mainly on the non-dominant side, as its lateral movement is associated with the lateral stability of the body during gait (Hsiang S.H. and Chang C., 2002). The stride was divided into a braking and a propulsive phase of the anterior-posterior ground reaction force. Six young healthy adults participated in the study. All components of the GRF were collected and analyzed using a Kistler force platform. Also, the kinematics provided the medio-lateral motion of the center of mass throughout the strides as they were collected and processed using the Vicon Nexus. The results showed that although asymmetries existed in every variable, the additional load did not increase the observed differences between the two legs. Also, the asymmetries were not consistent across the subjects in the vertical components of the force and the relative impulses. On the contrary, the propulsive impulse was significantly larger in the dominant limb. The center of mass mainly traveled on the dominant side which was not expected. Overall, power generation is associated with the dominant limb. However, power absorption and stability functions are unlikely to be a feature of the non-dominant limb based on this study. This conclusion can also be supported by the direction of the asymmetry observed in the center of mass lateral oscillation.

Key Words: Laterality, Asymmetry, Gait, Limb-Dominance, Center-of-Mass

Introduction

The human body presents a specific characteristic when it performs various movements. The scientific term for this phenomenon was first introduced as “laterality” and according to Schenk (1980) it is “*the functional dominance of one limb or one side of the human body over the opposite limb or side*” (In: Salonikidis K., 2002). Laterality lies on the fact that the two sides of the human body differ principally. Each side is controlled by the contra-lateral brain hemisphere. Although the origin of this phenomenon is yet to be found, its functional effects regarding many movement tasks, like writing and kicking, have been documented (Gabbard C. and Hart S., 1996).

In the case of lower limbs, the lack of fundamental knowledge regarding their lateralisation leads to a behavioral approach in order to document and generalise their roles and differentiation. Sadeghi H. et al. (1997), based on observation, pointed out in their study that one lower limb has mainly power absorption behavior while the other has mainly power generation behavior. In earlier studies these functions have been appointed to the left and right leg respectively, as were observed in large sample groups (Matsusaka N. et al, 1985, Hirokawa S., 1989). These studies support the fact that the dominant leg is responsible for the propulsion during the displacement of the human body while the non-dominant leg is responsible for supporting the bodyweight and maintaining balance.

Like other movements, gait has stabilising and mobilising features. However, unlike other motor skills like kicking a ball or jumping, gait requires a more symmetrical sequence of movements of the two sides, due to the continuity of its coordination. In normal gait, the movements of the two legs seem identical and several studies present findings that corroborate this. The vertical and horizontal ground reaction forces, joint angle time histories, EMG patterns of lower limb muscles and energy consumption were found to be symmetrical in relative studies (Claeys R., 1983, Hamill et al, 1984, Hannah R.E. et al. 1984, Chou L.S. et al. 1995, Hesse S. et al. 1997, Wall, J.C. and Turnbull, G.I 1986, Pierotti, S.E et al., 1991, Arsenault A.B., 1986).

On the contrary, there are several studies which indicate gait asymmetries. Many of them have measured the same variables with the ones that reported symmetry and came to different conclusions (Arsenault A.B. 1986,

Ounpuu S. and Winter D.A, 1989). Law H.T. (1987) found asymmetry in the velocities, stride lengths and stride times between the two lower limbs. Also, Seeley M.K. et al. (2008) investigated the vertical and anteroposterior GRFs and found that the propulsive impulse of the dominant limb is 7% larger than the non-dominant limb in fast speed gait, a fact which partially verifies the observations of Matsusaka N. et al. (1985).

The Center of Mass (CoM) as a major determinant of gait is being reasoned in the early study of Saunders J.B. et al. (1953), where its movement is considered to be the resultant action of all the ground reaction forces applied upon the human body and thus, it is feasible to observe the patterns developed throughout any activity by just measuring the change of every variable relatively to the CoM: *“ideally, the CoM can be regarded as the summation of all forces acting upon the body”* (Saunders J.B. et al. 1953).

The study of the motion of the CoM was used for the analysis of asymmetric gait. One study which is particularly related to the current project reported asymmetries in the lateral, vertical and anterior posterior oscillations of the CoM within the gait cycle (Crowe A. et al., 1995).

Objectives

The aim of the project was to investigate the gait of young healthy adults under the effect of large evenly distributed loads and test the assumption of existing asymmetries between the two lower limbs during the activity, under the effect of large evenly distributed loads.

Materials and Methods

Subjects

Seven young adult males (weight =76.66 kg $\pm$ 10, height =1.79 cm $\pm$ 5 cm, age =23.8 $\pm$ 2.9 years) were initially recruited and one of them was excluded due to scoliosis. Five participants had a dominant right leg and one had a dominant left. Anthropometric information of the participants is given in Appendix B (Table 4). All subjects have given their informed consent (Appendix A).

Leg dominance test

Functional limb dominance was determined according to the method described by Hoffman M et al. (1998). The method consists of three functional tests: ball kick, step up and balance recovery. Three trials for each test were conducted. The leg that was used in most of the trials was defined as the dominant lower limb. In the ball kick test, the subjects were instructed to kick a soccer ball and send it accurately through a pair of cones placed 1 meter apart from each other and 10 meters away from the subject. Accuracy was not considered a criterion but the leg which kicked the ball was the dominant limb for this test. In the step-up test, the subjects were asked to step onto a 20 cm high chair. Similarly, the dominant limb was the one which was used to step and rise. The balance recovery test requires the subject to be nudged to his back in order to lose his balance towards his back. In this case, the leg used to regain balance was considered as the non-dominant. (Appendix B, Table 3).

Data collection and experimental procedure

The *V-MAX™ 75 lb. Long Weight Vest* was used for adding the extra load and distribute it evenly. The participants were instructed to walk around the lab until they felt comfortable with the weight and adjust their gait pattern before the walking trials.

The choice of backpacks was rejected, as it has been shown that backpack load over 20% of bodyweight causes excessive trunk inclinations and it consequently alters the gait pattern (Singh T. and Koh M., 2008).

The CoM motion was calculated through kinematic data which were collected using eighteen VICON MX infrared cameras pointing at a six-meter walkway in the Loughborough University Biomechanics lab. The system was capturing at 100 Hz, suitable for a slow activity such as gait (Whittle M.W., 1996). The simplicity of the movement would normally require five to six cameras (Kadaba M.P. et al, 1990) but in this case more were needed to capture markers which were periodically covered by the weight-vests. The program used for capturing and processing the data was the VICON NEXUS 1.4.114. The cameras were calibrated using a five marker “L” frame wand. The volume origin was set using the same wand. The marker set that was selected for the kinematic analysis was the VICON Plug-In-Gait®. Nineteen segments were defined from the 35 markers (marker diameter: 6 mm) used for the specific model.

During the capturing sessions, participants were instructed to walk at self-preferred speed. Ten to fifteen trials for each condition were conducted with each subject. Nineteen satisfactory steps were obtained for each subject (two to four from each selected trial). The criteria for a successful step were the number of captured markers – in this case, the accurate calculation of the center of mass required all the markers to be visible. In some cases, the data were filtered by applying the “pattern fill” option available in NEXUS.

At the end of each capturing trial, subjects performed twenty-four steps in total (twelve for each leg) on a stable Type 9253B11 Kistler force platform, collecting data at 1000Hz. The three components of the ground reaction force, vertical (Fz), fore-aft (Fy) and lateral (Fx), were collected using the Kistler BioWare 3.2.6.104 software.

Data processing and analysis

The position of the CoM was acquired as an output from the Plug-In-Gait model as it was processed in NEXUS. For this calculation, additional anthropometric data were needed, which has been acquired before the start of the trials. The changed position of the clavicle and 10th thoracic vertebra markers (the markers were

placed on the vest), due to the use of the weight vests, altered the inertial properties of the model but did not affect the analysis. The two markers were aligned through the center of the torso and thus not causing lateral displacement of the thorax's segment center of mass.

Moreover, the analysis focused on the differences between the two sides and not on the investigation of the exact CoM path in space. The position of CoM in the lateral (x) axis was pulled from the output and processed in Microsoft EXCEL 2003. The values were normalized by the origin of the pelvis segment (midpoint of markers LASI and RASI, see Appendix E). After the normalisation, the lateral displacement of the CoM in space, was converted into an oscillation around its fixed position, resembling a sinusoidal curve (Fig. 1 and 2).

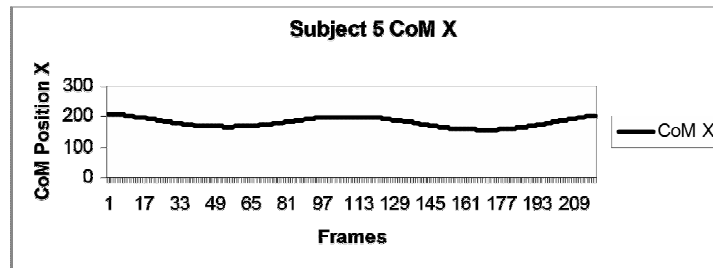


Fig. 1. Lateral displacement of the CoM of Subject 5 throughout 4 strides (Before normalization).

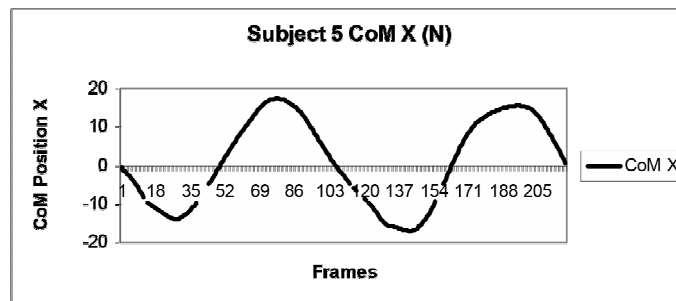


Fig. 2. Lateral displacement of the CoM of Subject 5 throughout 4 strides (After normalization).

The negative values correspond to the stepping of the left leg and the positive values to the right leg. The duration, average and peak displacements of the center of mass were calculated while it was travelling on each side, in order to investigate the symmetry of the oscillations. Longer durations and larger average and peak values are associated with increased stability function, since the lateral movement mainly contributes to balance. The standard deviations of the displacements were calculated in order to compare the variation of the displacement of the CoM while it travels on each side of the body. This will indicate the corrections made from the neuromuscular system to keep the CoM within stability regions (Hsiang S.H. and Chang C., 2002) and prepare it for propulsion. For the group statistical comparisons, CoM position was normalized by each subject's height (Brostrom E. et al, 2007).

The force data provided the values for the average and peak vertical force during the phase of heel-strike to mid-stance, and the average fore-aft force during the phase of mid-stance to toe-off. The medio-lateral forces were investigated as an average of the entire step, since their only role is to accelerate the body towards the opposite side to avoid loss of balance (Whittle M., 1995). The impulses were collected from the BioWare as the integral of the force curves. The impulses were used in order to investigate the appliance of forces with respect to time. In addition to that, the duration of the steps and phases was collected and compared.

The force values were normalised by the weight (mass×gravity) of each subject. Under loading conditions, the weight included the vest's additional mass. In order to compare the medio-lateral forces, the absolute values were taken as the two legs apply the lateral force in opposite directions. Impulses were normalised according to Hof A.L (1996), as shown in the equation below. The purpose of the impulse normalisation was to convert it into a dimensionless quantity and compare it as such.

$$\frac{I^2}{m^2 l_0 g} = \frac{|I|}{m \sqrt{l_0 g}}$$

I = impulse
 l_0 = leg length
 g = gravity (9.82 m/s^2)
 m = body mass

Statistical Analysis

To compare the parameters of the two sides in three different loading conditions, a two-way repeated measures ANOVA for within design was implemented using SPSS 17 (SPSS Inc., Chicago, IL, USA). The two within subject factors were: (1) Side with two levels, right and left and (2) Additional load, with three levels, normal, 20% and 50%. The specific analysis was appropriate to test the part of the hypothesis regarding the greater asymmetry as the load increases. A significant load by side interaction was evaluated for every dependent variable at a group and individual subject level. If the interaction was not significant then the comparisons between sides in every loading condition were conducted through the repeated measures ANOVA, using one

within factor with two levels (right-left). This test was preferred instead of paired t-tests, as it includes the Bonferroni correction.

When the interaction was significant, then post-hoc comparisons were performed. In the absence of a grouping variable, the post-hoc tests were conducted by breaking the repeated measures into a two by two instead of two by three design in order to evaluate the interaction of load by side in two different loading conditions. The test was again performed using only the factor of side to define the significance of the asymmetry in every condition. In the comparisons at group level, Subject 2 was excluded due to uncertainty regarding which is his dominant limb. Also, Subject 3 was excluded from the propulsive impulse and step phase durations comparisons, due to the excessive asymmetry he presented (up to 80% and 45% respectively). In the case of the standard deviation of the CoM positions, the comparisons were performed with F-tests using MedCalc 11.3 (MedCalc Software, Mariakerke, Belgium), (Appendix I, Figs.7 to 12). An alpha value of 0.05 was used for all statistical tests. In addition, the equation called “Symmetry Index”, proposed by Robinson et al. (1987, In: Sadeghi H. et al., 2000), was used to present a clear picture of the asymmetry level in each subject. The equation provides the difference of the two legs in the form of percentage difference:

$$SI = \frac{(X_s - X_i)}{0.5(X_s + X_i)} \times 100\%$$

SI: Symmetry Index
X_s=Right leg value
X_i=Left leg value

Results

The statistically significant bilateral differences of the ground reaction forces and the center of mass lateral oscillations, at group level, are presented in Tables 1 and 2 respectively. The differences for each individual can be seen at Appendix C (Tables 5 and 6). The differences as a percentage are presented in Appendix D (Table 7).

Table 1. Group comparisons for GRF in the three loading conditions. Fz: Vertical GRF, FzMAX: 1st peak of the Fz, Iz: Vertical impulse, Fy: Anterior-posterior GRF, Iy: Anterior-posterior impulse, Fx:

Medio-lateral GRF, Ix Medio-lateral impulse, HM t: Heel-strike to mid-stance duration, MT t: Mid-stance to toe-off duration, Step t: Stride duration, D: Dominant leg, ND: Non-dominant leg, *: Significant load by side interaction.

Group Comparisons	Fz*	FzMAX	Iz*	Fy*	Iy*	Fx	Ix	HM t	MT t	Step t
Normal	-	-	-	-	D>ND	D>ND	D>ND	-	-	-
20%	-	-	-	D>ND	D>ND	D>ND	D>ND	-	-	-
50%	D>ND*	D>ND	ND>D	D>ND	D>ND	D>ND	D>ND	ND>D	D>ND	-

A significant load by side interaction was detected for the average vertical force (Fz) and the support impulse (Iz) during the weight acceptance and weight transfer phases ($F_{(1,59)}=3.38$, $p=0.032$ and $F_{(1,59)}$, $p=0.012$ respectively). Significant load by side interaction was also detected for the anterior-posterior force (Fy) and the propulsive impulse (Iy) during the push-off phase ($F_{(1,59)}=4.4$, $p=0.017$ and $F_{(1,47)}=5.12$, $p=0.019$ respectively). Post hoc analyses revealed significant asymmetries in the Fz, in favor of the dominant limb ($F_{(1,59)}=7.59$, $p=0.008$) at 50% loading condition. The asymmetry of the support impulse was also found to be significant at the same loading condition but in favor of the non-dominant limb ($F_{(1,59)}=13.952$, $p=0.000$). The posterior force (Fy), presented asymmetries at both 20% and 50% loading conditions in favor of the dominant limb ($F_{(1,59)}=15.66$, $p=0$ and $F_{(1,59)}=18.89$, $p=0$ respectively). The propulsive impulse (Iy) of the dominant limb was significantly larger than the non-dominant in all three loading conditions ($F_{(1,47)}=24.993$, $p=0$, $F_{(1,47)}=31.79$, $p=0$ and $F_{(1,47)}=10.98$, $p=0.002$ for Normal, 20% and 50% respectively). The differences in propulsive impulse though varied significantly ($SD_{Normal}=6.46$, $SD_{20\%}=8.48$, $SD_{50\%}=34.72$), with one of the participants reaching up to 80% asymmetry in favor of the dominant limb (Subject 3). Another participant (Subject 2) had significant differences in favor of the non-dominant limb (4.5% to 12.5%). In the other force parameters, no significant load by side interaction was detected. However, there were differences between the lower limbs. Asymmetries were observed in the vertical braking force (FzMAX) at 50% loading condition ($F_{(1,59)}=11.44$, $p=0.001$). In medio-lateral forces and the relative impulses, the dominant side was significantly greater across the group in all load conditions but they varied between subjects (see Appendix C). Heel-strike to midstance and mid-stance to toe-off durations presented asymmetries too. At group level, heel-strike to mid-stance phase duration was significantly larger for the non-dominant limb in 50% load condition ($F_{(1,47)}=5.35$, $p=0.025$), while mid-stance to toe-off duration was greater in the dominant limb ($F_{(1,47)}=5.22$, $p=0.027$) in the same load condition.

Table 2. Group comparisons for the CoM lateral oscillation. Time: Duration the CoM remained over each leg, Average: Mean CoM displacement over each leg, Peak: Maximum CoM displacement over each leg. D: Dominant leg, ND: Non-dominant leg, *: Significant load by side interaction

Group CoM X	Time*	Average*	Peak*
Normal	D>ND	D>ND	-
20%	-	D>ND	D>ND
50%	D>ND	-	D>ND

Asymmetries were also detected in the CoM oscillations, as they were investigated by means of time spent over each leg, average and peak displacement and standard deviations. All the analysed variables presented consistent asymmetry, with the exception of one participant whose asymmetries between legs varied across the variables (Subject 5), the group had clear domination of one side over the other in all variables (Table 2). The CoM path over the dominant side occupied significantly longer time of the whole step than the non-dominant in normal gait and under the effect of additional 50% of bodyweight load ($F_{(1,94)}=33.635$, $p=0$ and $F_{(1,94)}=43.783$, $p=0$ respectively). The average displacement of the CoM over the dominant leg was significantly larger than the displacement over the non-dominant in normal and 20% loading condition ($F_{(1,94)}=74.27$, $p=0$ and $F_{(1,94)}=55.96$, $p=0$ respectively). A similar pattern appeared in the peak values of CoM lateral displacement ($F_{(1,94)}=35.69$, $p=0.000$ in 20% of load and $F_{(1,94)}=61.21$, $p=0$ in 50% of load). The variance (Standard Deviation) of the CoM lateral displacement was significantly greater when CoM traveled over the dominant side of the body. Subject 2 presented, similarly to the ground reaction forces, the asymmetries in the opposite manner in all CoM variables (Non-Dominant>Dominant). Finally, it is essential to note that none of the observed significant load by side interactions presented a linear direction.

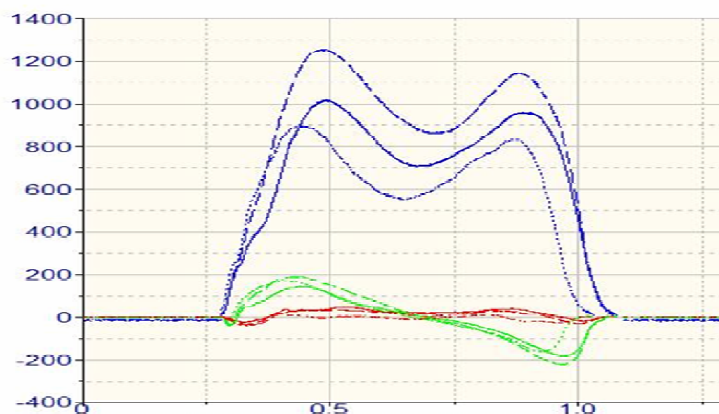


Fig. 3. BioWare data showing the GRF curve of the three loading conditions Normal, 20% and 50% (lower, middle and higher respectively), as they were merged for the left leg trials of Subject 3.

Discussion

The additional load did not alter the general gait pattern as documented in the GRF curves (Fig. 3). The original hypothesis predicted increasing asymmetries with additional load in the GRFs and the CoM oscillations. Although in some of the variables the asymmetries appeared at different level between loads, they did not necessarily increase gradually along with it (Fig. 4 and 5), a fact which consequently rejects that part of the hypothesis. It is worth mentioning the case of Subject 2, who produced results opposite to the hypothesis and to the other subjects. In addition, serious doubts were raised regarding the direction of his laterality during the leg dominance tests. Specifically, the ball kicking test takes for granted one's familiarity with it, as it is considered to be a common skill. However, as concerns Subject 2, this was not true. This issue raises questions regarding the reliability of the leg dominance tests and highlights the need for more sophisticated procedures to define the direction of laterality.

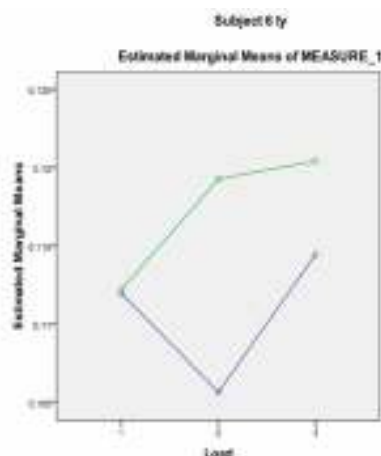


Fig. 4. SPSS Output. Means for propulsive impulse (I_y) for the two legs in all three loading conditions (1-Normal, 2-20%, 3-50% of bodyweight. Side 1 and 2 are right and left respectively) of subject 5.

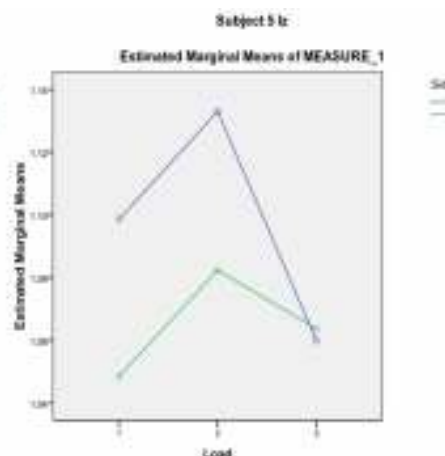


Fig. 5. SPSS Output. Means for vertical impulse (I_x) for the two legs in all three loading conditions (1-Normal, 2-20%, 3-50% of bodyweight. Side 1 and 2 are right and left respectively) of subject 3.

If the asymmetries are investigated without respect to additional weight, then the anterior-posterior GRF and the propulsive impulse confirm the relative part of the hypothesis. The pattern of these variables was consistent across the subjects and presented significantly larger values in the dominant leg. That fact partially supports the theory about limb dominance and appoints the propulsive function to the dominant limb. Moreover, the findings are consistent with the ones in the studies of Matsusaka N. et al. (1985) and Seeley M.K. et al. (2008). On the other hand, vertical braking force and support impulse did not present the expected asymmetries. Although at group level there were significant differences, at individual level the asymmetries were not consistent. This, along with the small sample, does not allow generalisation. The support function of the non-dominant limb cannot be proven by these findings. The findings are corroborating the ones Seeley M.K. presented in their study. The same authors also mentioned that in a relative frequently cited study (Hirokawa S., 1989) there is an apparent typographical error which leads to the false impression that the support function of the non-dominant limb is confirmed.

CoM traveled mainly over the dominant limb which suggests that the dominant side may be responsible for coordinating the movement of the CoM on the transverse plane and therefore, stabilise the body against lateral “fall”. This argument is supported by the similar asymmetries that were observed in the average and peak displacement of the CoM throughout the stride. Although the results partially refute the hypothesis, they confirm the findings from the analysis of the ground reaction forces and impulses. In the study of Hsiang S.H. & Chang C. (2002), it is stated that during the swing phase of the gait cycle the body is unstable because there is no double support and the body tends to fall forward and laterally. The neuromuscular system controls this kind of “fall” by sending commands to the responsible muscles to maintain the CoM within specific regions of the three planes. These regions are called “stability regions”.

As mentioned earlier, successful gait depends on speed, strength, inertial parameters of the body and neural response. In the above study, this statement is becoming more specific by noting that these parameters can define the size and shape of the stability regions. Moreover, the same authors concluded that the GRFs can change so they can be adjusted to an apparent alteration of the shape and size of the stability regions. The asymmetries found in the medio-lateral forces and impulses corroborate this. Higher displacement to the dominant side could develop the need for increased movement initiation to the opposite side. This is further concurred by the discrepancies in standard deviations of the CoM position in space. The higher variance of the CoM positions over the dominant side may suggest that the neuromuscular system performs more actions in order to “correct” the CoM motion while it is outside the base of support and thus avoid any excessive displacement and coordinate it within the stability regions. An example of such neuromuscular behavior, are the abductive actions of the tensor fascia latae muscle, during mid-stance, which prevents excessive pelvic tilt and keeps the CoM within the vertical and lateral stability regions (Whiting W. & Rugg S., 2006).

An important conclusion deriving from the present study is that impulse can be a more reliable indicator of stabilization and propulsive functions as it takes into account the duration of the force appliance and thus rules out any misinterpretation due to briefly applied large GRFs that can vary among trials. This argument is corroborated by the asymmetries found in heel-strike to mid-stance and mid-stance to toe-off durations, at group level, whilst whole step duration did not present differences between the two legs.

Conclusion

The findings of the present study suggest that a different approach might be needed for investigating the apparent power-absorption behavior of the non-dominant leg during able-bodied gait. The braking vertical force (1st vertical peak) and the weight extinction phase (2nd vertical peak) were analysed as one. In future research, it might be appropriate to analyse the step in more than two parts, in order to examine these two phases distinctively. To include a more detailed analysis of the CoM motion, the synchronisation of the kinematic and kinetic data will be essential. As it became evident, it was problematic to distinct between the phases of the stride based on video recordings. A pair of synchronised force platforms or a treadmill will be more reliable for the determination of the stride phases. Moreover, any symmetrical behavior appeared in the study does not necessarily imply functional symmetry of the two lower extremities, as kinematic and kinetic bilateral equivalence may be the result of greater muscular activity of one side, thus an electromyographic approach of gait asymmetry would be enlightening. Finally, the main weakness of the project lies on the small sample group. High variation in the presented asymmetries will not be a problem if larger sample is used.

To date, the assumption that large evenly distributed loads can reveal the different function of the two legs during gait, which would be unclear otherwise, was rejected by the findings since asymmetries appeared independent of load in every variable. The consistent asymmetry in favor of the dominant side in the forward impulse suggest that the propulsive function in normal gait can indeed be a feature of the dominant side of the human body. On the other hand, the non-significant asymmetries in the force variables during the stabilising phases of the step do not support the assumption of power absorption behavior of the non-dominant limb. On top of that, the CoM oscillation suggests the opposite, as the asymmetries were in favor of the dominant side.

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Signed (Subject) Date

In the presence of:

Name

APPENDIX B

Leg Dominance Tests	Subject 1	Subject 2	Subject 3	Subject 4	Subject 5	Subject 6	Subject 7
Ball Kick	R	R	R	R	R	L	R
Bench Step-up	R	R	R	R	R	L	R
Balance Recovery	L	L	L	L	R	L	R

Table 3. Leg dominance tests results. R: Right leg, L: Left leg.

Anthropometric Data	Subject 1	Subject 2	Subject 3	Subject 4	Subject 5	Subject 6	Subject 7
Body Mass (kg)	72.9	85.8	77.3	66.1	86.6	74.3	73.6
20%	14.58	17.16	15.46	13.22	17.32	14.86	14.72
50%	36.45	42.9	38.65	33.05	43.3	37.15	36.8
Height (mm)	1750	1850	1822	1755	1833	1769	1780
Inter-ASIS Distance (mm)	235	267.5	259	240	239	256	239
Dominant Leg (mm)	R	R	R	R	R	L	R
							Scoliosis
	Right	Left	Right	Left	Right	Left	Right
Leg Length (mm)	800	798	900	893	865	866	848
	840	852	852	825	830	827	827
Knee Width (mm)	95	95	100	102	101	97	93
	93	101	101	91	91	91	100
	91	100	99				
ASIS-Trochanter Dis (mm)	96	94	100	105	106	102	80
	79	101	98	105	108	102	103
Ankle Width (mm)	73	76	70	74	76	74	72
	73	72	77	77			
Shoulder Offset (mm)	50	43	59	56	42	45	36
	40	60	61	52	50	40	40
Elbow Width (mm)	67	62	69	67	73	71	70
	69	75	75	71	71	69	68
Wrist Width (mm)	52	55	56	55	60	60	56
	57	58	60	53	58	57	57
Hand Thickness (mm)	36	35	38	39	33	35	31
	31	40	41	34	32	40	44

Table 4. Anthropometric data

APPENDIX C

	Fz	FzMAX	Iz	Fy	Iy	Fx	Ix	HM t	MT t	Step t
Subject 1	-	*	L>R	R>L*	R>L	R>L	R>L	L>R	R>L	-
Subject 1 20%	-	*	-	R>L*	-	-	-	-	-	-
Subject 1 50%	-	R>L*	L>R	R>L*	R>L	-	-	L>R	R>L	-
Subject 2	-	-	R>L	L>R	L>R*	-	-	R>L	*	R>L*
Subject 2 20%	-	R>L	-	-	L>R*	-	-	-	L>R*	*

Subject 2 50%	-	R>L	-	-	L>R*	-	-	-	L>R*	*
Subject 3	*	L>R*	L>R*	-	*	R>L	R>L	*	R>L*	R>L*
Subject 3 20%	*	*	L>R*	-	*	R>L	R>L	*	*	*
Subject 3 50%	R>L*	R>L*	L>R*	R>L	R>L*	R>L	R>L	L>R*	R>L*	*
Subject 4	-	-	-	R>L*	*	R>L	R>L	-	-	-
Subject 4 20%	-	-	-	R>L*	R>L*	-	-	-	-	-
Subject 4 50%	-	R>L	-	*	*	R>L	R>L	-	-	-
Subject 5	R>L	-	R>L*	-	R>L*	L>R	L>R*	*	-	R>L*
Subject 5 20%	-	-	*	R>L	R>L*	-	*	*	-	*
Subject 5 Yo 50%	-	-	*	-	*	-	*	L>R*	L>R	L>R*
Subject 6	L>R	L>R	L>R	*	L>R*	R>L	-	L>R	R>L*	*
Subject 6 20%	L>R	L>R	L>R	L>R*	L>R*	-	-	-	*	*
Subject 6 50%	-	-	-	*	*	-	-	-	L>R*	*

Table 5. Individual comparisons for GRF in the three loading conditions. Fz: Vertical GRF, FzMAX: 1st peak of the Fz, Iz: Vertical impulse, Fy: Anterior-posterior GRF, Iy: Anterior-posterior impulse, Fx: Medio-lateral GRF, Ix Medio-lateral impulse, HM t: Heel-strike to mid-stance duration, MT t: Mid-stance to toe-off duration, Step t: Stride duration, . D: Dominant leg, ND: Non-dominant leg, *: Significant load by side interaction.

	CoM X	Time	Average	Peak	STDV
Subject 1	R>L	R>L	R>L	-	
Subject 1 20%	R>L	R>L	R>L	R>L	
Subject 1 50%	R>L	R>L	R>L	R>L	
Subject 2	L>R	L>R	L>R*	L>R	
Subject 2 20%	L>R	L>R	L>R*	L>R	
Subject 2 50%	L>R	L>R	L>R*	L>R	
Subject 3	L>R*	L>R*	L>R*	-	
Subject 3 20%	L>R*	L>R*	L>R*	L>R	
Subject 3 50%	*	*	*	-	
Subject 4	R>L*	R>L	R>L*	R>L	
Subject 4 20%	R>L*	R>L	R>L*	R>L	
Subject 4 50%	R>L*	R>L	R>L*	R>L	
Subject 5	R>L*	R>L*	*	-	
Subject 5 20%	L>R*	L>R*	L>R	L>R	
Subject 5 50%	*	*	*	R>L	
Subject 6	L>R	L>R	L>R	L>R	
Subject 6 20%	L>R	L>R	L>R	L>R	
Subject 6 50%	-	L>R	L>R	L>R	

Table 6. Individual comparisons for the CoM lateral oscillation. Time: Duration the CoM remained over each leg, Average: Mean CoM displacement over each leg, Peak: Maximum CoM displacement over each leg. D: Dominant leg, ND: Non-dominant leg, STDV: Displacement standard deviation, *: Significant load by side interaction.

APPENDIX D										
% Difference	Fz	FzMAX	Iz	Fy	Iy	Fx	Ix	HM t	MT t	Step t
Subject 1	-7.34	0.60	-12.35	6.07	10.70	15.57	15.65	-5.00	4.84	-0.64

Subject 1 20%	-2.53	-1.79	-5.83	39.81	11.37	50.25	49.55	-1.70	6.22	0.00
Subject 1 50%	-1.09	2.33	-6.94	17.67	24.73	-1.16	-1.31	-5.70	7.30	-0.16
Subject 2	-0.53	1.87	3.91	-5.86	-4.54	-13.31	-14.28	4.80	1.78	3.40
Subject 2 20%	0.71	3.88	0.16	-2.57	-5.04	-1.27	-1.94	-0.27	-2.20	-1.12
Subject 2 50%	1.47	5.52	3.66	-2.65	-12.43	1.70	-0.33	2.66	-8.87	-2.69
Subject 3	-0.53	-2.38	-7.58	4.90	12.38	70.82	69.87	-2.02	7.64	2.32
Subject 3 20%	0.71	-0.01	-4.99	11.19	4.49	88.44	86.61	-2.02	3.00	0.43
Subject 3 50%	11.51	2.25	-19.27	42.91	80.18	54.67	50.05	-30.46	45.24	-0.91
Subject 4	0.16	1.88	-1.97	7.41	4.98	37.57	35.43	-7.94	-2.00	-5.93
Subject 4 20%	-1.48	0.19	-0.61	8.99	5.41	28.69	25.98	1.20	-3.18	-0.86
Subject 4 50%	0.44	2.92	0.12	-1.37	0.19	39.92	37.63	0.21	1.68	0.88
Subject 5	2.30	-1.26	4.67	-4.43	6.99	-21.25	-25.70	2.50	2.78	2.60
Subject 5 20%	1.65	-3.31	4.76	5.01	4.60	7.07	7.05	3.10	-0.24	1.58
Subject 5 Yo 50%	1.66	-0.81	-0.42	3.01	-2.66	11.98	3.08	-2.57	-3.84	-3.11
Subject 6	-2.00	-4.66	-3.77	-2.79	-0.16	7.11	6.14	-2.07	3.80	0.61
Subject 6 20%	-2.24	-4.57	-4.70	-11.70	-12.11	13.52	10.28	0.43	-0.28	0.08
Subject 6 50%	-0.97	-2.56	-1.97	-0.88	-5.09	6.59	3.33	-1.76	-4.47	-2.98

Table 7. Discrepancies between the two lower limbs in the form of percentage as the where calculated by the Symmetry Index (SI) equation proposed by Robinson et al (1987, In: Sadeghi H. et al, 2000). Negative values correspond to greater mean values for the left leg.