



Side does not matter in healthy young and older individuals – Examining the importance of how we match limbs during gait studies

Erik Kowalski^a, Danilo S. Catelli^a, Mario Lamontagne^{a,b,*}

^a School of Human Kinetics, University of Ottawa, Ottawa, ON, Canada

^b Department of Orthopedic Surgery, The Ottawa Hospital, Ottawa, ON, Canada

ARTICLE INFO

Keywords:

Gait
Walking
Biomechanics
Kinematics
Kinetics
Spatiotemporal
Symmetry
Aging
Limb matching

ABSTRACT

Background: Various methods exist when comparing gait data between groups and include the analysis of a single limb, or taking an average of both limbs. Evidence exists suggesting that both limbs are not symmetrical, so statistical differences may exist in biomechanical variables when comparing gait with different limb-matching methods.

Research question: Does limb-matching method have an effect on statistical outcome when comparing biomechanical variables during a gait task?

Methods: This retrospective study compared forty participants separated into a younger and older group as they completed a gait task. Twenty-five commonly used biomechanical variables were compared between the two groups using four different limb-matching methods: (i) average of both limbs; (ii) dominant limb; (iii) non-dominant limb; (iv) random limb. A mixed linear model was used to compare all the biomechanical variables between the younger and older group using the different limb-matching methods.

Results: Limb-matching methods only had a significant effect for 1/25 variables examined. Group effects between the younger and older groups were more prevalent, with the most significant effects occurring at the ankle joint.

Significance: Limb-matching methods do not have a direct effect on biomechanical outcomes when comparing gait in healthy young and old groups. Gait is cyclical, so limb symmetry is often assumed. However, if the complexity of the task increases, or when comparing against groups with impaired gait, both limbs may behave differently, so limb-matching method may become more crucial.

1. Introduction

Gait is a basic requirement of daily life, and a major determinant of independence and quality of life [1]. However, gait is frequently impaired by a variety of musculoskeletal and neurological conditions, or surgical intervention (e.g. osteoarthritis, Parkinson's, stroke, total knee arthroplasty, etc.). In rehabilitation, gait receives a lot of attention due to its importance on restoring patients' independence [2]. To understand how gait changes from impairment to rehabilitation, it is often necessary to use healthy individuals as a comparison.

Walking may seem like a simple task, but is a complex motor skill requiring several inter-linked pathways from the cortex to the muscles [3]. There is a large interaction involving the central nervous system and various muscles in order to maintain the body upright, while at the same time moving in a smooth, rhythmical motion. Since gait in healthy individuals is seen as smooth and rhythmical, gait symmetry is often

assumed in the literature for the sake of data collection and analysis [4]. This simple assumption could be one of the primary reasons why many gait studies rely either on unilateral data collection [5–7] or an average of the left and right limb [8–10]. However, in these studies gait symmetry was not tested as it was assumed.

Before determining if gait is symmetrical or asymmetrical, it is essential to establish a definition of gait symmetry. Previously gait symmetry has been defined as a perfect agreement between the actions of the lower limbs [11]; the definition we prefer for gait symmetry is no statistical differences noted on parameters measured bilaterally [12]. Gait studies which have examined gait symmetry have either confirmed gait symmetry [13,14], or have found differences in gait parameters between both limbs [15,16]. With many studies in contradiction with each other, perhaps our reliance on unilateral or averaged left and right limbs during gait studies is incorrect.

When relying on unilateral data, such as using only the left or right

* Corresponding author at: 200 Lees Avenue, Room E020, Ottawa, ON, K1N 6N5, Canada.

E-mail address: mlamon@uottawa.ca (M. Lamontagne).

<https://doi.org/10.1016/j.gaitpost.2018.10.008>

Received 1 May 2018; Received in revised form 10 September 2018; Accepted 8 October 2018

0966-6362/ © 2018 Elsevier B.V. All rights reserved.

limbs, the researcher is also assuming that both limbs are similar. However, as with limb dominance in the upper extremity (i.e., handedness), functional asymmetries between the lower-limbs have been documented in tasks other than walking [17,18]. The idea of limb dominance is that the two hemispheres of the human brain are functionally dissimilar [4,17]. Differences between the dominant and non-dominant limbs have been made based on the roles of the lower limbs. The foot used in activities is the dominant foot, whereas the foot providing the stability and postural support is the non-dominant foot [19]. Other terms used in the literature to differentiate limbs have been the mobilization and stabilization, which represent the dominant and non-dominant limbs, respectively [19–21]. For continuity and simplicity, we will use the terms dominant and non-dominant limbs.

With certain tasks, there is a clear difference between the dominance of lower limbs (e.g., kicking a ball) [17,18]. With gait, it is not as clear, since it depends on which definition of symmetry is used and what variables are studied. However, researchers continue to use various limb-matching methods when comparing between subjects. These different methods may change the statistical outcome of the studies. When using gait data of healthy subjects to compare to impaired gait, such as those with osteoarthritis or a prosthetic joint in one limb, the method used to match the limb may be even more important to the statistical outcome. The purpose of this study was to explore various limb matching methods and its effect on the statistical outcome when comparing gait biomechanics between a younger and older group.

2. Methods

Data was collected from an ongoing standardized database that includes gait data of healthy individuals who were collected since 2009. The original study that the participants were volunteers was approved by the Research Ethics Board at the University and they provided written informed consent prior to participation in the study.

Participants were selected from the database if they were free from lower-limb injury and had no musculoskeletal or neurological disorder which would negatively impact gait. A total of 76 participants were eligible for inclusion in the study. From this cohort, participants were selected if they had a preferred walking speed (PWS) between 1.30 to 1.50 m/s. A total of 40 participants were included and were separated into two groups based on their age: a younger group (ages 23–44) and an older group (ages 54–81) (Table 1). For each participant, the dominant limb was identified as the preferred limb used to kick a ball [22].

Spatiotemporal and kinematic parameters of gait were measured using a 10-camera Vicon System (MX-13, Oxford Metrics, Oxford, UK) sampled at 200 Hz, and two Bertec force platforms (FP4060, Bertec Corporation, Columbus, USA) sampled at 1000 Hz. Participants were outfitted with 45 passive-reflective markers according to the University of Ottawa Motion Analysis Model (UOMAM) [23]. Following a static trial, all participants performed a standardized walking task: three trials of walking at their preferred speed, across a level 10 m walkway which included the two force plates in the middle.

Gait data were processed using Vicon Nexus 2.6 software (Oxford Metrics, Oxford, UK). Trajectories were filtered using a Woltring filter

Table 1

Group mean demographic values. The group mean (SD) for each age group is provided for all of the recorded demographic variables.

| | Younger | Older |
|--------------------------------------|-----------|-----------|
| Range (years) | 23–44 | 54–81 |
| Number (n) | 20 | 20 |
| Age (years) | 30.5(7.2) | 63.4(6.4) |
| Sex (male/female) | 8/12 | 9/11 |
| Body Mass Index (kg/m ²) | 24.3(2.9) | 25.4(3.3) |
| Dominant Limb (right/left) | 19/1 | 18/2 |

Table 2

Spatiotemporal, kinematic, and kinetic variables of interest.

| Variable | Unit | Abbreviation |
|--|---------|--------------|
| <i>Spatiotemporal</i> | | |
| Walking speed normalized to leg length | | |
| Stride time | (s) | |
| Step time | (s) | |
| Stride length normalized to leg length | | |
| Step length normalized to leg length | | |
| <i>Kinematics</i> | | |
| Peak hip flexion angle during stance | (°) | HA1 |
| Peak hip extension angle | (°) | HA2 |
| Peak hip flexion angle during swing | (°) | HA3 |
| Peak knee flexion angle | (°) | KA1 |
| Peak ankle dorsiflexion angle | (°) | AA1 |
| Peak ankle plantar flexion angle | (°) | AA2 |
| <i>Kinetics</i> | | |
| Support moment at early stance | (Nm/kg) | SM1 |
| Support moment at late stance | (Nm/kg) | SM2 |
| Peak hip flexion moment | (Nm/kg) | HM1 |
| Peak hip extension moment | (Nm/kg) | HM2 |
| Peak knee flexion moment | (Nm/kg) | KM1 |
| Peak knee extension moment | (Nm/kg) | KM2 |
| Peak ankle dorsiflexion moment | (Nm/kg) | AM1 |
| Peak ankle plantar flexion moment | (Nm/kg) | AM2 |
| Peak hip power absorption | (W/kg) | HP1 |
| Peak hip power generation | (W/kg) | HP2 |
| Peak knee power absorption | (W/kg) | KP1 |
| Peak knee power generation | (W/kg) | KP2 |
| Peak ankle power absorption | (W/kg) | AP1 |
| Peak ankle power generation | (W/kg) | AP2 |

with a mean standard error of 15 and force platform data were filtered using a 4th order (zero lag) Butterworth filter with a cut-off frequency of 10 Hz. Gait events were identified with the help of the force plates and the walking trials were modeled with the UOMAM. Data were exported to Matlab R2016a (MathWorks, Natick, USA) to extrapolate spatiotemporal, kinematic and kinetic variables of interest.

A total of 25 commonly used variables in biomechanics were selected for analysis (Table 2). Group means for all these variables were compared between the younger and older groups with the following limb matching methods: (i) average of both limbs; (ii) dominant limb; (iii) non-dominant limb, and (iv) limb selected at random.

All statistical analyses were done using SPSS v.20 software (IBM Corporation, Armonk, USA) to perform a mixed linear model (MLM) of the relationship between age group and limb matching method on the various biomechanical variables. As fixed effects, we entered age group (young/old) and the four limb-matching methods into the model. Participants were entered as a random effect, and alpha was set at 0.05 for all tests. For any significant differences between limb-matching methods, a *Bonferroni* correction was used to identify where the significant difference occurred. Using the MLM, we were able to determine if there was a statistical effect of group, limb-matching method, as well as the interaction between them.

3. Results

The complete results comparing the different limb matching methods for all the variables of interest are located in the Supplementary material in the Appendix (Tables A1 to A4). In general, most variables did not have a significant limb matching method effect. The only variable which had a significant limb matching method effect was peak ankle plantar flexion moment, which had a significant difference between the dominant and non-dominant limb matching methods ($p = 0.014$) (Fig. 1). Several variables, primarily at the ankle joint, had a significant group effect between the young and old groups (Table 3). For the spatiotemporal variables, walking speed normalized to leg length, stride time, and step time all had significant group effects

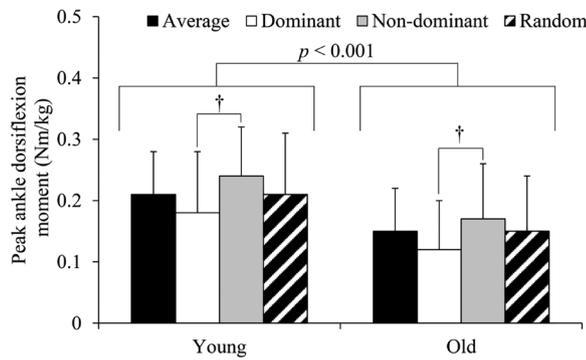


Fig. 1. Peak ankle dorsiflexion moment (Nm/kg) of younger and older participants during a gait trial compared using various limb-matching methods. Mixed linear model group effect is indicated in the figure, and a significant limb-matching method is represented by a †.

between the young and old groups (Table A1). None of the other biomechanical variables examined had a significant group-limb matching method interaction.

4. Discussion

Researchers in biomechanics use a variety of limb-matching methods to compare data amongst groups. The aim was to identify if limb-matching method has a statistical effect on the biomechanical variables. Many gait studies rely either on unilateral data collection [5–7] or an average of the left and right limb [8–10] when making comparisons. These methods are so often used because we think of gait a cyclical motion, therefore, symmetrical motion [4]. Gait symmetry is when no statistical differences exist on parameters measured bilaterally [12]. Although the consensus on gait symmetry is still ongoing, it is important to understand the statistical impact of matching limbs has on the outcomes during gait studies.

Table 3

Group mean ankle joint kinematic and kinetic values during gait in a young and older group. The group mean (SD) for each of the four limb matching methods is provided for the spatiotemporal variables. The *p*-values are calculated from the linear mixed model where group and limb matching methods were fixed variables, and participants were set as random variables. Where applicable, a significant limb matching method effect was adjusted with a *Bonferroni* correction to identify where the significant difference occurred (†). Interaction effect is the Group*Limbs Matching Method effect.

| Variable | Limb Matching Methods | Group | | Group Effect (p – value) | Limb Matching Method Effect (p – value) | Interaction Effect (p – value) |
|---|-----------------------|-----------------|---------------|--------------------------|---|--------------------------------|
| | | Young Mean (SD) | Old Mean (SD) | | | |
| Peak ankle dorsiflexion (°) | Average | 10.8 (3.3) | 10.7 (3.0) | 0.961 | 0.534 | 0.995 |
| | Dominant | 10.1 (3.3) | 10.2 (3.8) | | | |
| | Non-dominant | 11.5 (4.3) | 11.2 (3.6) | | | |
| | Random | 10.5 (3.5) | 10.5 (3.8) | | | |
| Peak ankle plantar flexion (°) | Average | 22.3 (6.0) | 20.0 (4.3) | 0.014 | 0.639 | 0.498 |
| | Dominant | 24.2 (5.8) | 19.9 (4.4) | | | |
| | Non-dominant | 20.5 (9.6) | 20.0 (5.1) | | | |
| | Random | 22.7 (6.7) | 20.2 (4.2) | | | |
| Peak ankle dorsiflexion moment (Nm/kg) | Average | 0.21 (0.07) | 0.15 (0.07) | < 0.001 | 0.025 | 0.999 |
| | Dominant | 0.18 (0.10) | 0.12 (0.08) | | | |
| | Non-dominant | 0.24 (0.08) | 0.17 (0.09) | | | |
| | Random | 0.21 (0.10) | 0.15 (0.09) | | | |
| Peak ankle plantar flexion moment (Nm/kg) | Average | 1.13 (0.14) | 0.86 (0.14) | < 0.001 | 0.596 | 0.251 |
| | Dominant | 1.07 (0.17) | 0.89 (0.15) | | | |
| | Non-dominant | 1.19 (0.17) | 0.85 (0.19) | | | |
| | Random | 1.10 (0.15) | 0.83 (0.26) | | | |
| Peak ankle power absorption (W/kg) | Average | 0.71 (0.37) | 0.91 (0.22) | 0.001 | 0.947 | 0.909 |
| | Dominant | 0.71 (0.39) | 0.87 (0.30) | | | |
| | Non-dominant | 0.72 (0.42) | 0.95 (0.21) | | | |
| | Random | 0.74 (0.38) | 0.87 (0.27) | | | |
| Peak ankle power generation (W/kg) | Average | 3.45 (0.77) | 2.84 (0.50) | < 0.001 | 0.671 | 0.811 |
| | Dominant | 3.30 (0.82) | 2.82 (0.59) | | | |
| | Non-dominant | 3.61 (0.90) | 2.84 (0.55) | | | |
| | Random | 3.34 (0.84) | 2.77 (0.51) | | | |

We used a MLM to compare a total of 25 commonly used biomechanical variables in a young and old group completing a walking task. The benefit of the MLM was that it allowed for identification of significant differences between the young and old group, and between the four limb matching methods. Although the means varied between the different limb matching methods, the MLM confirmed that the various limb-matching methods were statistically the same (*p* > 0.05). Only a single variable, peak ankle dorsi-flexion moment, had a significant difference between the dominant and non-dominant limb matching methods (Fig. 1). Therefore, when comparing gait in healthy groups, limb-matching the groups is not necessary as they will produce similar statistical outcomes.

Although there are studies which confirm that gait is symmetrical [13,14] or asymmetrical [15,16], our findings would confirm that gait is symmetrical except for peak ankle dorsi-flexion moment. We asked our participants to walk in a straight line at a self-selected pace. Although gait is a complex motor skill [3], when moving in a straight line, without any obstacles, it is as smooth and rhythmical as a task can be. When performing more complex movements or sport-specific skills which involve more motor skills such as kicking a ball, the lower limbs may perform differently, so selecting appropriate limb-matching methods during these tasks may be more crucial.

Our cohort included young and old healthy adult participants. Gait studies often include analyses on participants whose gait is impaired by musculoskeletal and neurological conditions (e.g. Parkinson’s, stroke, osteoarthritis), or surgical interventions (total hip arthroplasty, total knee arthroplasty). For these participants, gait symmetry should not be assumed, so when comparing them against healthy controls, limbs should be matched more carefully.

Gait analysis is more commonly being used before and after orthopedic intervention to provide objective evidence on the joint biomechanical function [24]. Researchers are encouraged to use a control group to make comparisons with, instead of using the contralateral limb, as this limb’s function may be altered because of compensating for the affected limb [24]. Our findings suggest that limb-matching

methods in healthy adult participants do not affect statistical outcome, so regardless of which limb-matching method researchers select, their comparison will be valid.

Many studies have compared young adults' gait with older adults' gait. In general these studies have identified that older adults have a slower walking speed, shorter step length, reduced range of motion in the lower extremity joints, and a distal to proximal shift in joint torques [25–28]. Although limb-matching methods were not specified in all instances, it is still evident that gait of older adults is different from younger adults. Our findings were generally in agreement, as the MLM identified significant age group effect for many variables. The younger group walked significantly faster than the older group even after normalizing walking speed to leg length. The faster walking speed resulted in a significantly shorter stance and stride time. Ankle joint kinetics were significantly lower in older adults than younger adults [27,28]. Reductions in ankle joint mobility and strength may be the cause of the age-related differences observed between young and old adults; therefore, future studies could investigate this further.

This study has certain limitations which must be addressed. First, more than 90% of our participants identified as right limb dominant when asked for their preferred limb when kicking a ball [22]. One should not assume that using only the right limb will always provide the same statistical outcome as the dominant limb, because if a cohort has primarily left-limb dominant participants, this may not be the case. Second, we compared healthy young and old groups, so differences in biomechanical variables using different matching-limbs may exist in participants whose gait is impaired. The preferred walking speed which was homogeneous among the participants could also attenuate the limb asymmetry.

5. Conclusions

In conclusion, our findings have shown that the limb-matching methods do not have a direct influence on the statistical outcome when comparing gait of younger and older healthy individuals. The dominant and non-dominant limb matching methods had only a significant effect on the peak ankle dorsi-flexion moment. This study showed that there were mainly no significant limb-matching method effects; confirming that both the dominant and non-dominant sides were symmetrical for the healthy participants. If the cohort changes to include participants with impaired gait (e.g. stroke, Parkinson's, osteoarthritis, or joint arthroplasty), both limbs may not perform identically. However, if using a control group for comparison with an impaired gait group, the way limbs are matched between groups is not critical. Therefore, future studies are necessary to investigate participants with impaired gait.

Author Contributions

All authors have made substantial contributions to all of the following: (1) the conception and design of the study, or acquisition of data, or analysis and interpretation of data, (2) drafting the article or revising it critically for important intellectual content, (3) final approval of the version to be submitted.

Conflicts of interest statement

The authors have no conflicts of interest to declare.

Acknowledgements

This work was supported in part by the CAPES foundation of Brazil

(1098-13/06); the Canadian Institutes of Health Research (97778A), and Natural Sciences and Engineering Council of Canada (106769-2013).

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi: <https://doi.org/10.1016/j.gaitpost.2018.10.008>.

References

- [1] A. Schmid, P.W. Duncan, S. Studenski, S.M. Lai, L. Richards, S. Perera, et al., Improvements in speed-based gait classifications are meaningful, *Stroke* 38 (2007) 2096–2100.
- [2] N.K. Latham, D.U. Jette, M. Slavin, L.G. Richards, A. Procino, R.J. Smout, et al., Physical therapy during stroke rehabilitation for people with different walking abilities, *Arch. Phys. Med. Rehabil.* 86 (2005) S41–S50.
- [3] R. Joffe, Gait disturbances, *Aust. Fam. Phys.* 21 (1992) 1437–1440.
- [4] H. Sadeghi, P. Allard, F. Prince, H. Labelle, Symmetry and limb dominance in able-bodied gait: a review, *Gait Posture* 12 (2000) 34–45.
- [5] P.R. Cavanagh, R.J. Gregor, Knee-joint torque during swing phase of normal treadmill walking, *J. Biomech.* 8 (1975) 337–8.
- [6] R.D. Crowinshield, R.A. Brand, R.C. Johnston, Effects of walking velocity and age on hip kinematics and kinetics, *Clin. Orthop. Relat. Res.* (1978) 140–144.
- [7] J.J. Eng, D.A. Winter, Kinetic-analysis of the lower-limbs during walking - What information can be gained from a 3-dimensional model, *J. Biomech.* 28 (1995) 753–758.
- [8] R.E. Hannah, J.B. Morrison, A.E. Chapman, Kinematic symmetry of the lower-limbs, *Arch. Phys. Med. Rehabil.* 65 (1984) 155–158.
- [9] S. Ounpuu, J.R. Gage, R.B. Davis, 3-Dimensional lower-extremity joint kinetics in normal pediatric gait, *J. Pediatr. Orthop.* 11 (1991) 341–349.
- [10] D.A. Winter, Kinematic and kinetic patterns in human gait - variability and compensating effects, *Hum. Mov. Sci.* 3 (1984) 51–76.
- [11] W. Herzog, B.M. Nigg, L.J. Read, E. Olsson, Asymmetries in ground reaction force patterns in normal human gait, *Med. Sci. Sports Exerc.* 21 (1989) 110–114.
- [12] L.A. Gundersen, D.R. Valle, A.E. Barr, J.V. Danoff, S.J. Stanhope, L. Snydermackler, Bilateral analysis of the knee and ankle during gait - an examination of the relationship between lateral dominance and symmetry, *Phys. Therapy* 69 (1989) 640–650.
- [13] J. Hamill, B.T. Bates, K.M. Knutzen, Ground reaction force symmetry during walking and running, *Res. Q. Exerc. Sport* 55 (1984) 289–293.
- [14] J.H.M. Vanderstraaten, P.J.M. Scholten, Symmetry and periodicity in gait patterns of normal and hemiplegic children, *Acta Morphologica Neerlandica-Scandinavica* 16 (1978) 135–.
- [15] K.D. Chatinier, R.H. Rozendal, Temporal symmetry of gait of selected normal human subjects, *Proceedings of the Koninklijke Nederlandse Akademie Van Wetenschappen Series C-Biological and Medical Sciences* 73 (1970) 353–+.
- [16] I. Singh, Functional asymmetry in the lower limbs, *Acta Anat.* 77 (1970) 131–138.
- [17] C. Gabbard, S. Hart, A question of foot dominance, *J. Gen. Psychol.* 123 (1996) 289–296.
- [18] C. Gabbard, M. Iteya, Foot laterality in children, adolescents, and adults, *Laterality* 1 (1996) 199–205.
- [19] M. Peters, Footedness - asymmetries in foot preference and skill and neuropsychological assessment of foot movement, *Psychol. Bull.* 103 (1988) 179–192.
- [20] C. Dargentpare, M. Deagostini, M. Mesbah, G. Dellatolas, Foot and eye preferences in adults - relationship with handedness, sex and age, *Cortex* 28 (1992) 343–351.
- [21] C. Gabbard, Foot lateralization and psychomotor control in 4-year olds, *Percept. Motor Skills* 68 (1989) 675–678.
- [22] J.P. Chapman, L.J. Chapman, J.J. Allen, The measurement of foot preference, *Neuropsychologia* 25 (1987) 579–584.
- [23] G. Mantovani, M. Lamontagne, How different marker sets affect joint angles in inverse kinematics framework, *J. Biomech. Eng.* (2017) 139.
- [24] M. Lamontagne, M.L. Beaulieu, D. Varin, P.E. Beaulé, Gait and motion analysis of the lower extremity after total hip arthroplasty: what the orthopedic surgeon should know, *Orthop. Clin.* 40 (2009) 397–405.
- [25] P. DeVita, T. Hortobagyi, Age causes a redistribution of joint torques and powers during gait, *J. Appl. Physiol.* 88 (2000) 1804–1811.
- [26] A. Gabell, U.S.L. Nayak, The effect of age on variability in gait, *J. Gerontol.* 39 (1984) 662–666.
- [27] J.O. Judge, R.B. Davis 3rd, S. Ounpuu, Step length reductions in advanced age: the role of ankle and hip kinetics, *J. Gerontol. Ser. A Biol. Sci. Med. Sci.* 51 (1996) M303–12.
- [28] D.C. Kerrigan, M.K. Todd, U. Della Croce, L.A. Lipsitz, J.J. Collins, Biomechanical gait alterations independent of speed in the healthy elderly: evidence for specific limiting impairments, *Arch. Phys. Med. Rehabil.* 79 (1998) 317–322.