Abstract

Background/Aims: The purpose of this study was to examine the intra-rater reliability of the Gait Real-time Analysis Interactive Laboratory (GRAIL) system during self-paced mode, in repeated gait analysis of healthy individuals.

Methods: Ten healthy male (age: 35.4 ± 13.3 yr; BMI: 25.2 ± 4.3) and 10 healthy female (age: 41.1 ± 16.4 yr; BMI: 24.5 ± 2.6) participants walked on a split-belt, self-paced treadmill. Each participant completed two gait assessments separated by an average of 7±3 days. Key gait kinematic, kinetic and spatial-temporal parameters were analysed. The interclass correlation Coefficient (ICC), Standard Error of Measurement (SEM) and Minimum Detectable Change (MDC) were calculated to evaluate the reliability of these gait parameters.

Findings: Results showed high repeatability of spatial temporal and excellent repeatability of kinematic and kinetic parameters in male and female groups. This is the first paper to evaluate the reliability of the GRAIL gait parameters for healthy females.

Conclusion: The findings suggest that the GRAIL system in self-paced mode is a good instrument to evaluate gait parameters for females as well as males.

Keywords: Reliability; Gait analysis; Instrumented treadmill; GRAIL; Self-paced.

Key points

- First paper to test the reliability of the GRAIL system for female gait analysis.
- “High” repeatability of spatial-temporal parameters for females.
- “Excellent” repeatability of spatial-temporal parameters for males.
- “Excellent” repeatability of males and females kinematic/kinetic parameters.

Reflective questions

- Should reliability of gait analysis be measured separately for male and female populations?
- If so, what are the factors that are likely to differ between the two populations?
- How does measuring reliability of gait analysis in clinical populations differ to its measurement in healthy populations?

Introduction

There is evidence (Astephen et al. 2008; Miyazaki et al. 2002) to suggest that walking mechanics may have a substantial impact on the progression of diseases of aging such as osteoarthritis. Gender differences in walking biomechanics have been identified with over-ground and instrumented treadmills (Cho et al. 2004; Riley et al. 2007), however there is limited evidence on gender differences for self-paced (SP) treadmill settings.

The Gait Real-time Analysis Interactive Laboratory (GRAIL, Motekforce Link, Amsterdam, the Netherlands) system measures and quantifies gait patterns in a virtual reality environment. It combines a fully instrumented treadmill with a self-paced (SP) option, as described by Sloot et al. (2014a). The treadmill is feedback-controlled which allows participants to walk at their preferred speed. Functioning in a SP mode is a novel approach comparable to over-ground walking (Geijtenbeek et al. 2011; Sloot et al. 2014a; 2014b). In addition, SP walking offers a major practical advantage as it is no longer necessary to establish the preferred walking speed prior to setting a fixed belt speed (Sloot et al. 2014b).

Recent literature (Liu et al. 2016; Sloot et al. 2014a; 2014b) has assessed the capability of the GRAIL system in gait analysis as well as its day to day reliability for males (Al-Amri et al. 2017). However, this work provides new insight in to exploring the reliability of the GRAIL system for females.

The literature is replete with information regarding gait differences between male and female (Callisaya et al. 2008; Kerrigan et al. 1998; Kobayashi et al. 2014). Given the overall movement differences between genders, it is essential to assess the reliability of the gait systems in male and female separately. Recent studies have reported gender effect on gait symmetry (Kobayashi et al. 2014) and spatial-temporal parameters (Callisaya et al.

2008). Meanwhile, biomechanical gait analysis is increasingly applied in rehabilitation settings to assist in therapeutic decision-making (Paquet et al. 2003; Yamada et al. 2006) and thus it is crucial to enhance our understanding of gait dynamics.

Wrisley et al. (2004) define reliability as an indication of the consistency of the measurements. As repeated gait measurements typically show some differences, these can be assumed to contain a proportion of error. However, gait reliability assessment enables researchers and clinicians to understand whether the difference refers to a real change or merely a change within the boundaries of Standard Error Measurements (Atkinson and Nevill 1998; McGinley et al. 2009).

The reliability of the GRAIL system for healthy individuals needs to be established before it can be used to identify abnormalities of joint function in different patients groups, especially in females as this has not been investigated before. Thus, the purpose of this study was to examine the intra-rater reliability of the GRAIL system during SP mode in repeated gait analysis of healthy male and female individuals.

Methods

Research participants and setting

Twenty participants with characteristics summarized in **table 1** walked on a split-belt instrumented treadmill, placed in a virtual environment with 160° semi-cylindrical projection screen and with a 10-camera Vicon MX optical infrared tracking system (Oxford Metrics, UK) **(Figure 1)**. Participants underwent two gait analysis sessions, separated by an average of 7±3 days. Inclusion criteria were: age between 18 and 90 years; healthy with no neurological or musculoskeletal conditions. Written informed consent was obtained prior to participation. The study was carried out in the Orthopaedic Research Institute at Bournemouth University, with ethical approval from Research Ethics Committee at Bournemouth University (ref 15005).

Characteristic for participants	**Female (N=10) mean (SD)**	**Male (N=10) mean (SD)**
Age, years	35.4 (±7.4)	41.1 (±8.3)
Height, cm	169.3 (±5.2)	178.9 (±13.3)
Mass, kg	78.2 (±7.1)	72.5 (±15.1)
BMI, kg/m	24.5 (±2.6)	25.2 (±4.3)

Table 1. Participants characteristics.

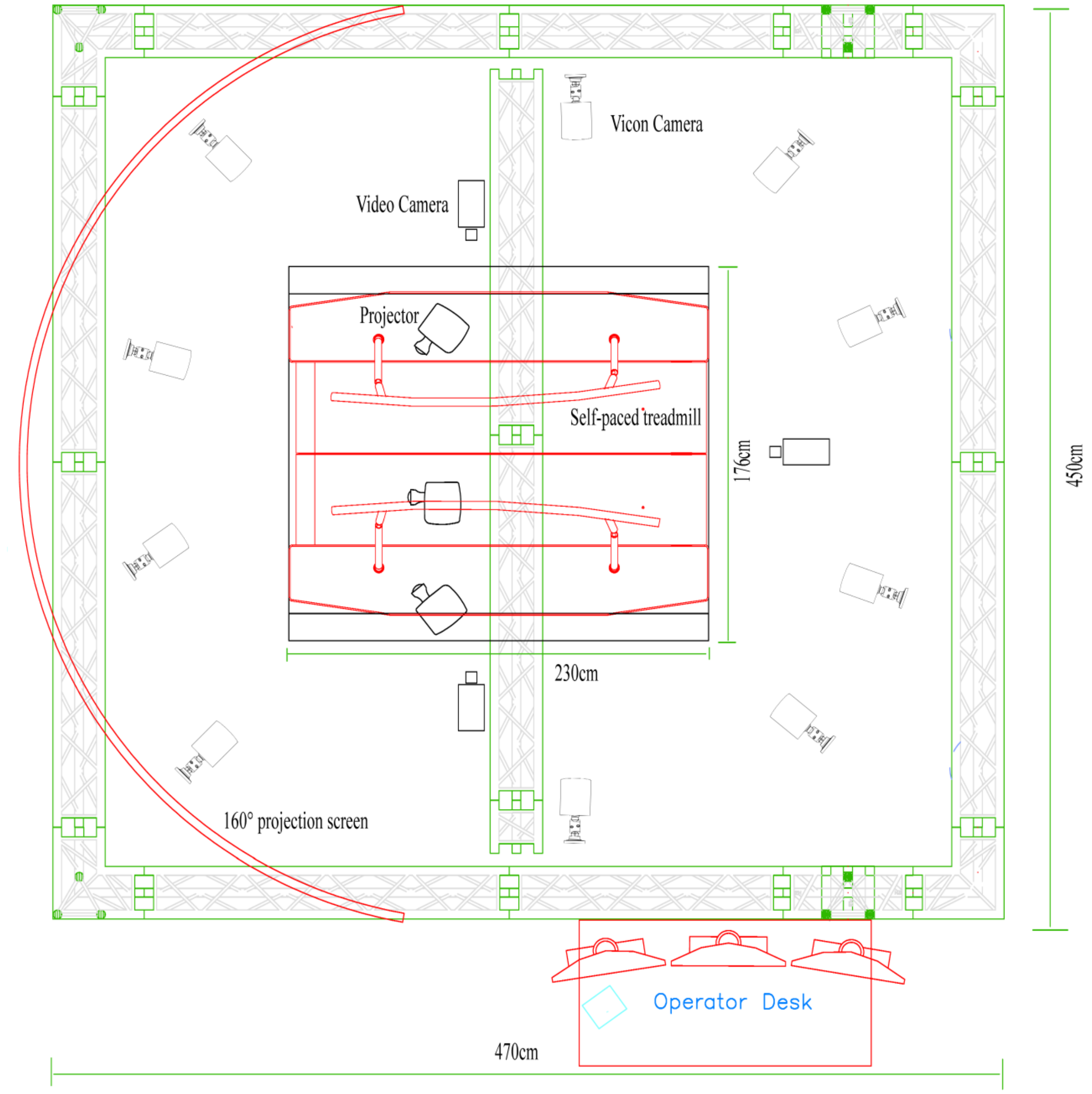

Figure 1: Orthopaedic Research Institute gait laboratory. Schematic illustrates the locations for VICON cameras, VR screen, projectors, and SP treadmill.

Measurement procedure

Participants were asked to wear a pair of comfortable walking shoes and tight clothing (such as cycling shorts or leggings) to ensure that markers could be placed on the optimum joint location for best accuracy. To ensure consistency, the same shoes and clothing were used in the first and the second session. Participants were fitted with 25 reflective markers using the Human Body Model (HBM) lower-body marker set (van den Bogert et al. 2013) as detailed in **Appendix 1**. The assessor was blinded to the results of the first session when undertaking the second session. Knee and ankle widths required for the HBM model were measured during each session. Moments were measured based on force sensors mounted underneath both treadmill belts (50 cm × 200 cm). Kinematic data of the lower extremities were collected via a passive marker motion capture system (Vicon, Oxford, UK) and synced at 200 Hz to the force data. All systems were integrated using D-Flow software (version 3.26, Motekforce Link, Amsterdam, the Netherlands) (Geijtenbeek et al. 2011).

Participants were positioned on the middle of the treadmill and wore a harness for safety. Participants were asked to walk for at least 6-minutes to adapt to SP treadmill walking (Al-Amri et al. 2017; Liu et al. 2017; Zeni and Higginson 2010). The SP mode was chosen in order to allow participants a more natural stride variability (Sloot et al. 2014b). Participants were able to self-adjust treadmill speed via a feedback-regulated algorithm in D-flow (Sloot et al. 2014b). Following the acclimatisation to the SP mode, participants walked for a minimum of 5 minutes and gait cycles (Herman et al. 2010) were recorded using D-Flow software. The testing procedure for the first session was replicated for the second session.

Measurement of outcomes

Marker and forceplate data were low-pass filtered at 6 Hz. Gait events detection was calculated based on foot markers (Zeni Jr et al. 2008). Ground reaction force data from heel contact to toe off were collected using integrated force plates (Forcelink, 12 channels, sample frequency 1000 Hz). Walking speed was derived from the GRAIL treadmill output in accordance with prior studies of the GRAIL system (Al-Amri et al. 2017; Sloot et al. 2014b). Vertical ground reaction forces were normalised by body weight and their first and second peaks values were calculated. To overcome the effect of gait initiating (standing to walking) and termination (walking to standing), means of each gait parameter were calculated from 50-310 seconds (full walking 360 seconds). Mean step length, mean stride time, mean stance, swing time, joint angle and joint moment parameters were processed and analysed in Matlab R2017a (the Mathworks Inc., USA). All cycles were screened visually and on the Gait Offline Analysis Tool (GOAT, version 2.3, Motekforce Link, Amsterdam, the Netherlands) for accuracy. As per other publications (Bridenbaugh and Kressig 2011; McGinley et al. 2009), and lack of consensus with regards to the selection of gait parameters for testing reliability (Lord et al. 2011), key clinical parameters including spatial-temporal, kinematics and kinetics moments for left and right limbs are reported in this study. This includes: Mean walking speed; mean step length; mean stride time; mean stance; swing time; Range of Motion (ROM) of hip flexion/extension, adduction/abduction; ROM of knee flexion/extension; peaks of hip flexion/extension moment; and peaks of knee flexion/extension moment. The ROM was calculated for a complete cycle by measuring the difference between the minimum and maximum joint angle.

Data analysis

SPSS statistics for Windows was used in the analysis (IBM, 2010). The assumption of normal data was evaluated using the Shapiro-Wilk test. Within gender reliability was assessed using a Related Samples Wilcoxon Signed Ranks Test with the significance level set at 0.05. It should be highlighted that multiple significance tests were carried out in the analysis (38 tests) so care should be taken accordingly with the statistical findings (Ranganathan et al. 2016). Systematic variation between gait parameters were analysed using 'Bland-Altman' plots for the first and second sessions (Bunce 2009). Correlation and agreement between gender groups were reported using formulae below:

$$Diff = (Mean\ Session\ 1) - (Mean\ Session\ 2) \qquad (1)$$

$$95\%\ \text{of LOA} = Diff \pm 1.96 \times SD_{Diff} \qquad (2)$$

Where $Diff$ is the mean difference between the two sessions and SD_{Diff} is the standard deviation of the $Diff$.

The interclass correlation Coefficient (ICC) method was used to analyse agreement between sets of gait parameters measurements in the first and second sessions for the male and female groups (Rankin and Stokes 1998). An ICC coefficient lower than 0.39 indicates poor reliability; between 0.4 and 0.59 indicates 'fair' agreement; between 0.6 and 0.79 'high reliability' and bigger than 0.8 was accepted as evidence of 'excellent' agreement (Bruton et al. 2000). For this calculation, a one way random model was chosen, with confidence intervals (CI) of 95% (Al-Amri et al. 2017). Measurement errors were evaluated by the Standard Error of Measurement (SEM), using formula (1). The SEM is used to estimate intra-individual variability and absolute repeatability as the ICC usually overlooks absolute repeatability (Al-Amri et al. 2017; Bruton et al. 2000). The SEM provides measurement error in the same unit as the original gait measurements,

$$SEM = SD1 \times \sqrt{1 - ICC} \qquad (1)$$

where SD1 is the standard deviation of the measurement from the first session.

The SEM was used to facilitate clinical interpretation of the gait measurements by calculating Minimum Detectable Change (MDC) (Flansbjer et al. 2005). A MDC at a 95% CI is calculated using formula (2). The MDC indicates whether a change observed between tests is a 'real' alteration rather than a 'random' variation in measurements (Wilken et al. 2012).

$$MDC = SEM \times 1.96 \times \sqrt{2} \qquad (2)$$

Results

Results of the mean, standard deviation and the mean difference for test-retest results of key spatial-temporal, kinematics and kinetic gait parameters for male and female participants are given in **Table 2**. The Wilcoxon rank test was carried out due to non-normal distribution of data and showed no-significant differences between the results for the female group except for peak hip flexion (p = 0.037). There was a significant difference in the male group for right step length (p = 0.013), left step length (p = 0.037), right swing time (p = 0.022) and left peak knee flexion/extension (p = 0.047). The mean difference was less than 0.03 measurement units for all of the spatial-temporal, less than 0.8° for the kinematic and less than 0.1 Nm/kg for the kinetic gait parameters in both male and female groups.

Repeatability assessments within male and female groups (ICC, SEM, MDC) for all gait parameters are summarized in **Table 3**. ICC values for all of the gait parameters in males show excellent repeatability (range 0.800 – 0.994). ICC values for all of the gait parameters except right step length (0.558), right stance time (0.677) and peak hip flexion/extension (0.494) in females show excellent repeatability (range 0.877 – 0.966).

SEM values are between 0.003 and 0.060 measurement units for all of the spatial-temporal gait parameters within male and female groups. MDC values are below 0.2 measurements unit for all of the spatial-temporal parameters and less than 4° and 0.38 Nm/kg for the kinematics and kinetics range of motion respectively. The 'Bland-Altman' plots shows good agreement between sessions for male and female groups (**Figure 2**) with most of the gait parameters within the 95% recommended LoA.

		Female				Male			
		MS1 (±SD)	**MS2 (±SD)**	***p***	**Diff (±SD)**	**MS1 (±SD)**	**MS2 (±SD)**	***p***	**Diff (±SD)**
Spatial-temporal Parameters									
Walking speed (m/s)		1.361 (0.214)	1.377 (0.223)	0.575	-0.015 (0.049)	1.407 (0.209)	1.457 (0.214)	0.059	-0.050 (0.074)
Step length (s)	Right	0.700 (0.059)	0.734 (0.071)	0.241	-0.033 (0.057)	0.740 (0.070)	0.757 (0.065)	0.013	-0.017 (0.024)
	Left	0.708 (0.071)	0.716 (0.083)	0.203	-0.008 (0.016)	0.734 (0.081)	0.752 (0.075)	0.037	-0.017 (0.025)
Stride time (s)	Right	1.066 (0.094)	1.604 (0.096)	0.959	0.002 (0.019)	1.057 (0.078)	1.041 (0.078)	0.059	0.016 (0.030)
	Left	1.066 (0.094)	1.065 (0.097)	0.959	0.001 (0.019)	1.057 (0.080)	1.044 (0.083)	0.059	0.014 (0.037)
Stance time (s)	Right	0.732 (0.081)	0.703 (0.077)	0.333	0.029 (0.060)	0.685 (0.053)	0.685 (0.061)	0.333	0.001 (0.037)
	Left	0.705 (0.075)	0.705 (0.078)	0.878	0.000 (0.014)	0.693 (0.070)	0.682 (0.065)	0.059	0.011 (0.023)
Swing time (s)	Right	0.359 (0.022)	0.361 (0.023)	0.173	-0.002 (0.004)	0.362 (0.019)	0.357 (0.019)	0.022	0.005 (0.006)
	Left	0.361 (0.022)	0.360 (0.021)	0.593	0.001 (0.005)	0.364 (0.021)	0.362 (0.021)	0.114	0.002 (0.008)
Kinematic joint range of motion									

Hip flex/ext (deg)	Right	30.254 (6.045)	30.440 (6.213)	0.508	-0.185 (0.742)	32.921 (9.470)	33.688 (9.836)	0.139	-0.767 (1.482)
	Left	28.648 (6.329)	29.092 (6.408)	0.169	-0.443 (0.914)	32.728 (9.604)	33.218 (9.915)	0.139	-0.490 (1.035)
Hip Abd/Add (deg)	Right	5.605 (2.614)	5.913 (2.964)	0.333	-0.309 (0.639)	8.257 (3.667)	8.457 (3.550)	0.285	-0.200 (0.507)
	Left	6.422 (2.684)	6.367 (2.942)	0.646	0.056 (0.331)	8.572 (5.428)	8.807 (5.496)	0.445	-0.236 (0.568)
Knee flex/ext (deg)	Right	48.956 (4.465)	48.737 (2.832)	0.799	0.219 (1.792)	45.132 (3.447)	45.095 (3.850)	0.959	0.036 (1.527)
	Left	46.881 (2.281)	47.140 (1.787)	0.445	-0.258 (1.033)	45.027 (3.276)	45.363 (3.701)	0.169	-0.336 (1.307)
Kinetics of joints moments									
Peak hip flex/ext (Nm/kg)	Right	0.855 (0.182)	0.832 (0.190)	0.799	-0.009 (0.064)	0.772 (0.138)	0.823 (0.138)	0.074	-0.051 (0.076)
	Left	0.832 (0.210)	0.955 (0.276)	0.037	-0.123 (0.222)	0.873 (0.249)	0.966 (0.367)	0.074	-0.093 (0.185)
Peak knee flex/ext (Nm/kg)	Right	0.418 (0.153)	0.420 (0.104)	0.799	-0.001 (0.039)	0.443 (0.114)	0.450 (0.132)	0.241	-0.007 (0.056)
	Left	0.420 (0.131)	0.438 (0.093)	0.139	-0.019 (0.039)	0.447 (0.156)	0.473 (0.160)	0.047	-0.026 (0.031)

Table 2. Mean, within gender results of the repeated gait spatial-temporal, kinematics joint range of motion, and kinetic joint moments.

		Female					Male				
		ICC	P_{ICC}	SEM	MDC	95%CI	ICC	*p*	SEM	MDC	95%CI
Spatial-temporal Parameters											
Walking speed (m/s)		0.975	<0.001	0.034	0.094	0.908 to 0.099	0.917	<0.001	0.060	0.167	0.720 to 0.978
Step length (s)	Right	0.558	<0.001	0.039	0.109	-0.035 to 0.866	0.911	0.031	0.021	0.058	0.700 to 0.977
	Left	0.978	<0.001	0.012	0.033	0.921 to 0.995	0.931	<0.001	0.021	0.059	0.762 to 0.982
Stride time (s)	Right	0.983	<0.001	0.012	0.034	0.936 to 0.996	0.937	<0.001	0.019	0.054	0.782 to 0.984
	Left	0.983	<0.001	0.012	0.034	0.936 to0.996	0.925	<0.001	0.021	0.059	0.744 to 0.981
Stance time (s)	Right	0.677	<0.001	0.046	0.128	0.157 to 0.907	0.840	0.008	0.021	0.059	0.506 to 0.957
	Left	0.984	<0.001	0.009	0.026	0.941 to 0.996	0.925	<0.001	0.017	0.046	0.743 to 0.981
Swing time (s)	Right	0.981	<0.001	0.003	0.009	0.930 to 0.995	0.919	<0.001	0.005	0.015	0.726 to 0.979
	Left	0.973	<0.001	0.004	0.010	0.902 to 0.993	0.927	<0.001	0.006	0.015	0.749 to 0.981
Kinematic joint range of motion											
Hip flex/ext (deg)	Right	0.993	<0.001	0.506	1.402	0.974 to 0.998	0.986	<0.001	1.121	3.106	0.949 to 0.997
	Left	0.988	<0.001	0.693	1.922	0.957 to 0.997	0.994	<0.001	0.744	2.062	0.976 to 0.998
Hip Abd/Add (deg)	Right	0.967	<0.001	0.480	1.330	0.882 to 0.992	0.990	<0.001	0.367	1.016	0.961 to 0.997
	Left	0.994	<0.001	0.230	0.636	0.978 to 0.999	0.994	<0.001	0.420	1.165	0.978 to 0.999
Knee flex/ext (deg)	Right	0.894	<0.001	1.454	4.030	0.652 to 0.972	0.921	<0.001	0.969	2.685	0.731 to 0.979
	Left	0.877	<0.001	0.800	2.217	0.604 to 0.968	0.932	<0.001	0.854	2.368	0.766 to 0.982

Kinetics of joints moments											
Peak hip flex/ext (Nm/kg)	Right	0.952	0.001	0.040	0.111	0.829 to 0.988	0.800	<0.001	0.062	0.171	0.408 to 0.945
	Left	0.494	0.001	0.135	0.375	-0.123 to 0.843	0.803	0.005	0.111	0.307	0.416 to 0.946
Peak knee flex/ext (Nm/kg)	Right	0.966	<0.001	0.028	0.078	0.877 to 0.991	0.905	<0.001	0.035	0.097	0.683 to 0.975
	Left	0.913	<0.001	0.031	0.085	0.706 to 0.977	0.969	<0.001	0.028	0.076	0.888 to 0.992

Table 3. Relative and absolute reliability within male and female groups.

Discussion

The purpose of this study was to examine the reliability of the GRAIL system during SP mode in repeated gait analysis of healthy male and female individuals. This is an essential consideration in both clinical and research utilization of quantitative gait analysis data. The results of this investigation demonstrate that almost all variables of interest exhibited high repeatability within gender groups. However, the findings on gender differences may provide new insight into gait biomechanics during a SP mode and may be important for both clinical and research studies in motivating the development of separate biomechanical reference databases for males and females.

The ICC range (0.840 to 0.937), the ‘Bland-Altman’ plots **(Figure 2)**, and small SEM and MDC values (< 0.06 & < 0.167 measurement unit, respectively) of males indicate excellent repeatability for the key spatial-temporal gait parameters. This is in agreement with Al-Amri et al. (2017), who only tested male participants.

This study was also designed to evaluate the reliability of the gait parameters for females. For the key spatial-temporal gait parameters, the ICC values (0.558 to 0.984) show a larger range. Right step length, and the right stance time show ‘high reliability’ agreements with ICC values 0.558 and 0.677 respectively. The small SEM values (range 0.003 to 0.046 measurement unit) indicate intra-individual reliability, however a larger range of MDC values (0.009 to 0.128 measurement unit) was found for the female group in contrast to the male group.

The ICC range (0.558 to 0.984), and small SEM and MDC values (< 0.06 & < 0.167 measurement unit, respectively) within male and female groups indicate an excellent repeatability for the key spatial-temporal gait parameters within genders.

The kinematic range of motion data also show excellent repeatability (ICC > 0.877) within both female and male groups. The SEM and MDC values (<1.454 & <4.030 measurement unit, respectively) for all of the range of motion parameters indicate that the measurement made by the GRAIL system is stable over time. These were confirmed by 'Bland-Altman' graphs finding **(Figure 2)**.

Males had larger hip extension/flexion and abduction/adduction range of motion and smaller knee extension/flexion compared to females and there was no significant difference across any of the parameters which are in accordance with Ko et al. (2011) study. The greater hip flexion in females may be the result of a greater stride in proportion to height, because peak hip flexion has been found to directly collate with stride (Murray et al. 1964; Murray et al. 1970).

A fair repeatability (ICC = 0.494) and significant difference between sessions ($p = 0.037$) for the female left peak hip flexion/extension, indicates a parameter which should be approached with caution. Overall the ICC range (0.800 to 0.969), with exception of female left peak hip flexion/extension, the 'Bland-Altman' plots **(Figure 2)** and small SEM and MDC values (< 0.135 & < 0.375 measurement unit, respectively) between male and female groups indicate a good repeatability for kinetic gait parameters.

Previous studies on gender difference in joint biomechanics during over-ground walking suggests that, on average, males walk at a higher speed with a shorter stride time compared to females (Finley and Cody 1970; Murray et al. 1964; Murray et al. 1970; Oberg et al. 1993). The results of our study demonstrate similar results during GRAIL analysis. A significant difference was seen for the right step length, and, for the right swing time of the male participant. This may be due to the fact that there was a large variability in the height of male participants (**Table 1**).

This work was conducted to test the reliability of the gait analysis of our GRAIL system, in order to support our future research in clinical and healthy populations. However, the study has limitations. The sample was a convenience sample which may affect the generalisability of findings. Additionally, these measurements of repeatability in gait assessment were conducted on a healthy population. Dominant leg was not recorded and so is not reported. In clinical studies this could be relevant, but in this study of a healthy population with the explicit aim of looking at reliability it was not considered essential to record. It is important to highlight that there is likely to be more variation in clinical populations, such as patients with chronic diseases; at risk of falls; and with increased frailty. However given the increased burden of undertaking repeatability tests; in most cases it is not feasible or ethical to conduct reliability studies in these populations. Inter-tester reliability was not investigated where participants are tested by different testers and multiple centres are included. Another limitation of this study is that the learning from walking on the SP treadmill when participants were first tested may have impacted on their results from the second testing. While SP treadmill walking has been validated for healthy subject during comfortable walking speed (Sloot et al. 2014b) further research is necessary to determine specific factors that may affect adaptability in SP treadmill walking.

In this study only a single-task situation was analysed. Recently, studies have indicated that changes in performance whilst dual tasking were significantly associated with an increased risk for falling amongst older adults, yet evidence is still lacking (Beauchet et al. 2009; Zijlstra et al. 2008). The use of GRAIL virtual reality features to analyse the reliability of gait parameters in SP mode while dual tasking is an interesting topic for future research.

Conclusion

All gait parameters investigated in this study demonstrated high to excellent test-retest reliability in male and female adults with the exception of kinetic peak hip flexion/extension for the female group which was assessed as fair. These findings illustrate that the GRAIL system in SP mode is a good instrument to evaluate gait parameters for both males and females. This is the first paper to establish these findings for female individuals. Future research is warranted with regard to the establishment of clinically relevant changes in different populations and settings.

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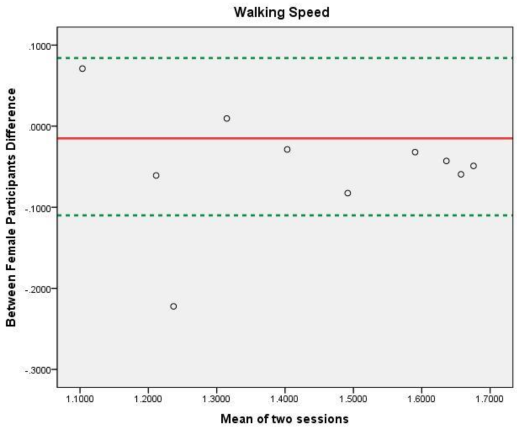
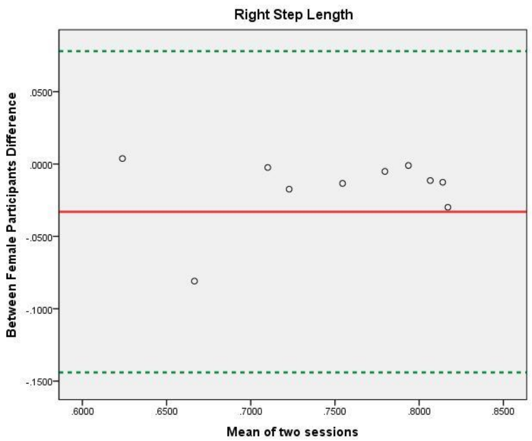
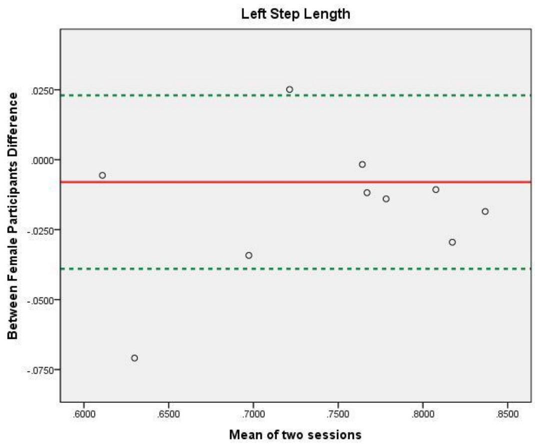
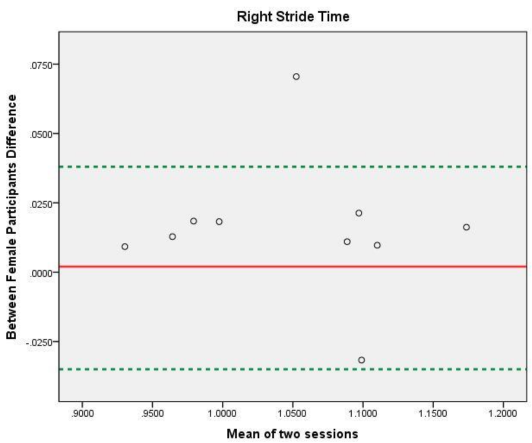
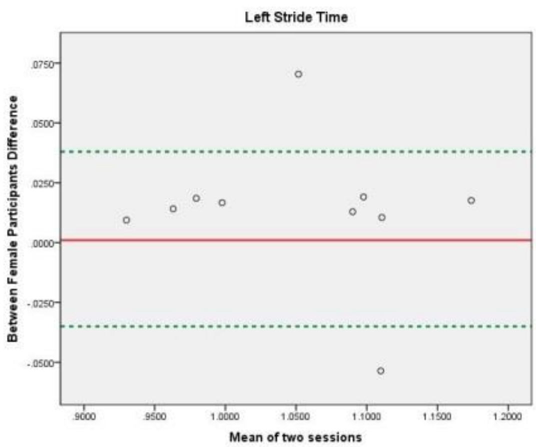
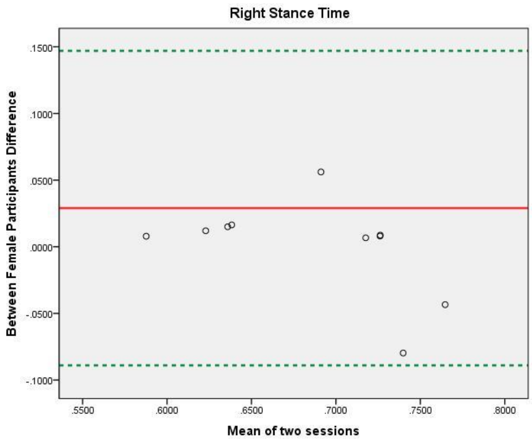

Walking Speed
Between Female Participants Difference
Mean of two sessions


Right Step Length
Between Female Participants Difference
Mean of two sessions


Left Step Length
Between Female Participants Difference
Mean of two sessions


Right Stride Time
Between Female Participants Difference
Mean of two sessions


Left Stride Time
Between Female Participants Difference
Mean of two sessions


Right Stance Time
Between Female Participants Difference
Mean of two sessions
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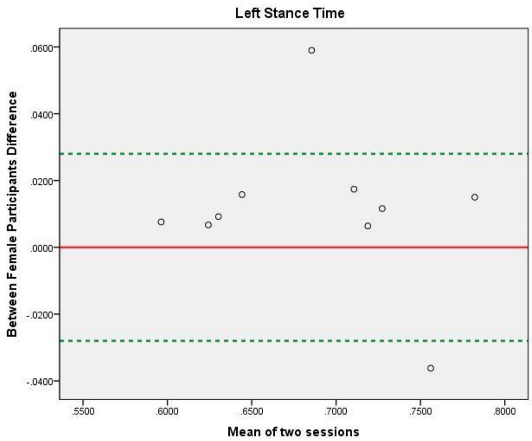
.1000
.0500
.0000
-.0500
-.1000
.5500
.6000
.6500
.7000
.7500
.8000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Between Female Participants Difference
Mean of two sessions
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.0000
-.0200
-.0400
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.6000
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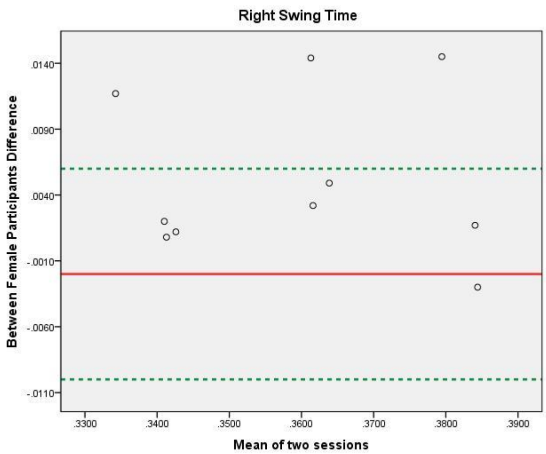
.7000
.7500
.8000


Right Swing Time
Between Female Participants Difference
Mean of two sessions
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.0090
.0040
-.0010
-.0060
-.0110
.3300
.3400
.3500
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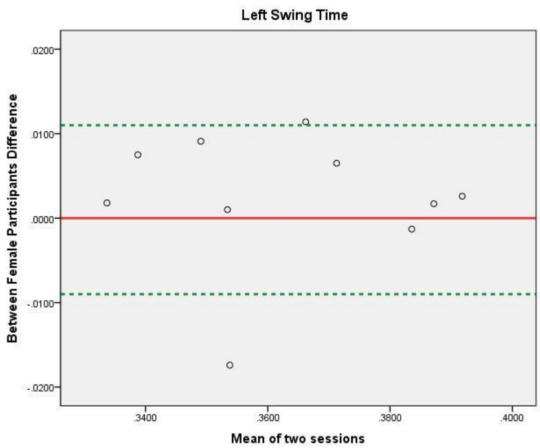
.3700
.3800
.3900


Left Swing Time
Between Female Participants Difference
Mean of two sessions
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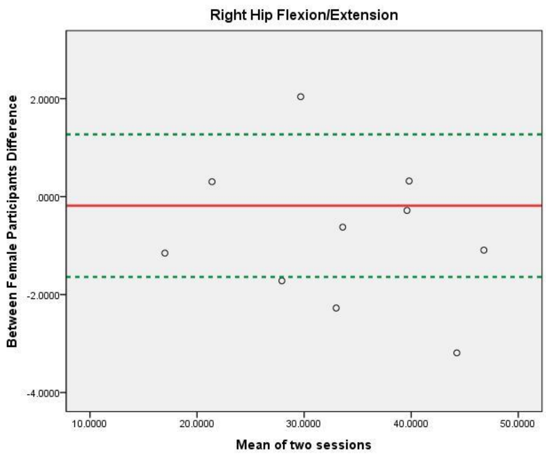
.0100
.0000
-.0100
-.0200
.3400
.3600
.3800
.4000


Right Hip Flexion/Extension
Between Female Participants Difference
Mean of two sessions
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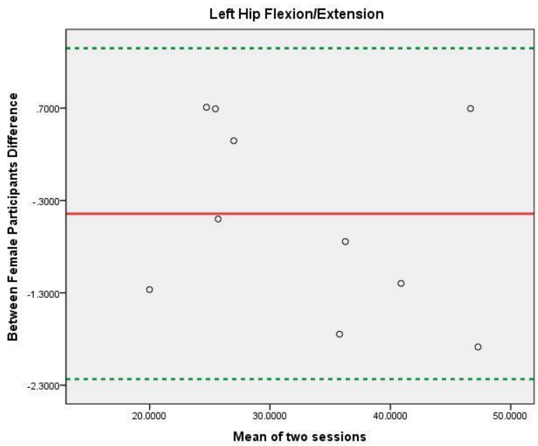
.0000
-2.0000
-4.0000
10.0000
20.0000
30.0000
40.0000
50.0000


Left Hip Flexion/Extension
Between Female Participants Difference
Mean of two sessions
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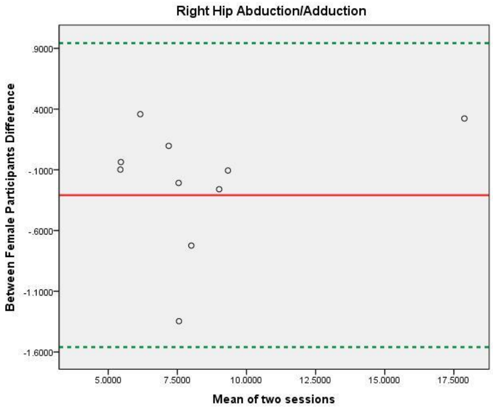
-1.3000
-2.3000
20.0000
30.0000
40.0000
50.0000


Right Hip Abduction/Adduction
Between Female Participants Difference
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.4000
-.1000
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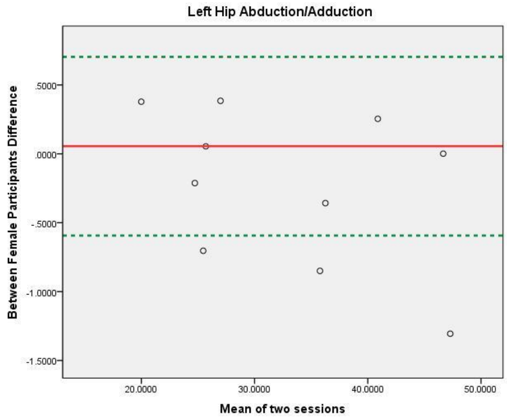
5.0000
7.5000
10.0000
12.5000
15.0000
17.5000
Mean of two sessions


Left Hip Abduction/Adduction
Between Female Participants Difference
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.0000
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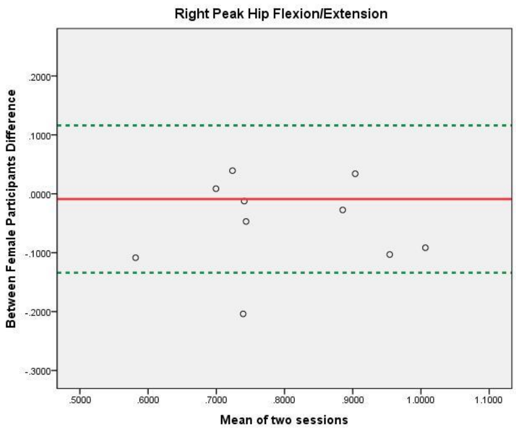
-1.0000
-1.5000
20.0000
30.0000
40.0000
50.0000
Mean of two sessions


Right Peak Hip Flexion/Extension
Between Female Participants Difference
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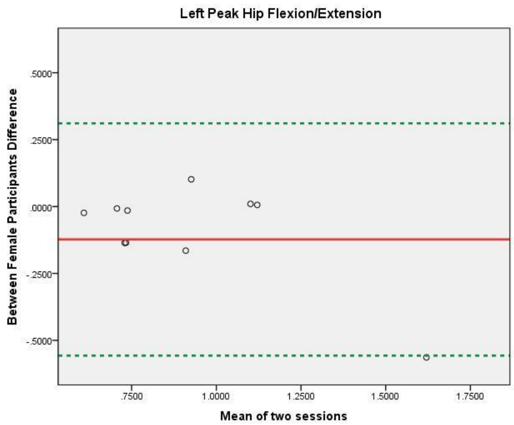
.1000
.0000
-.1000
-.2000
-.3000
.5000
.6000
.7000
.8000
.9000
1.0000
1.1000
Mean of two sessions


Left Peak Hip Flexion/Extension
Between Female Participants Difference
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.0000
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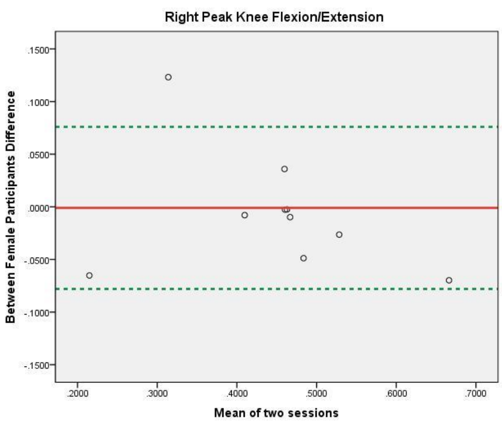
.7500
1.0000
1.2500
1.5000
1.7500
Mean of two sessions


Right Peak Knee Flexion/Extension
Between Female Participants Difference
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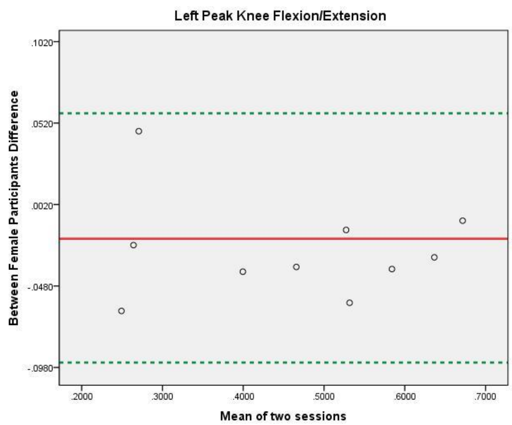
.2000
.3000
.4000
.5000
.6000
.7000
Mean of two sessions


Left Peak Knee Flexion/Extension
Between Female Participants Difference
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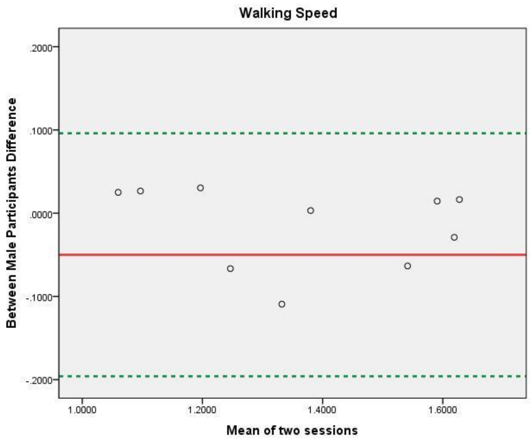
.2000
.3000
.4000
.5000
.6000
.7000
Mean of two sessions


Walking Speed
Between Male Participants Difference
.2000
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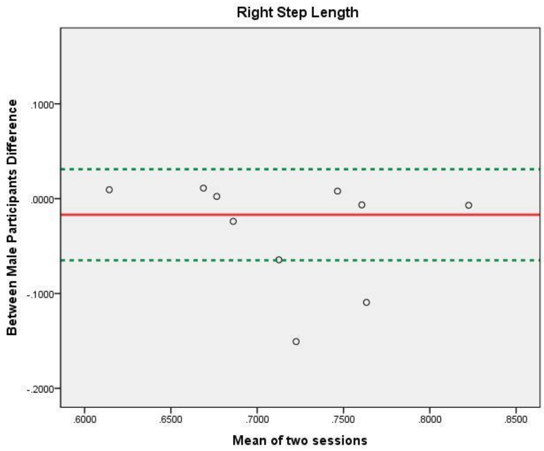
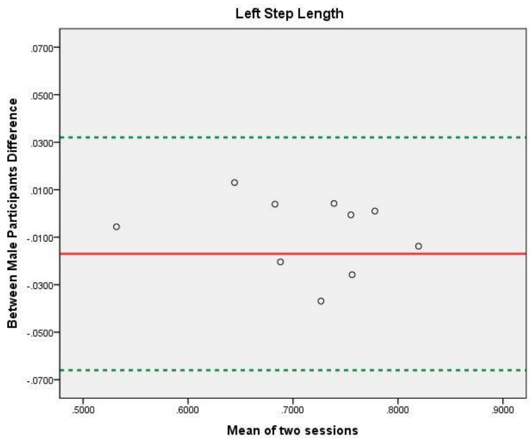
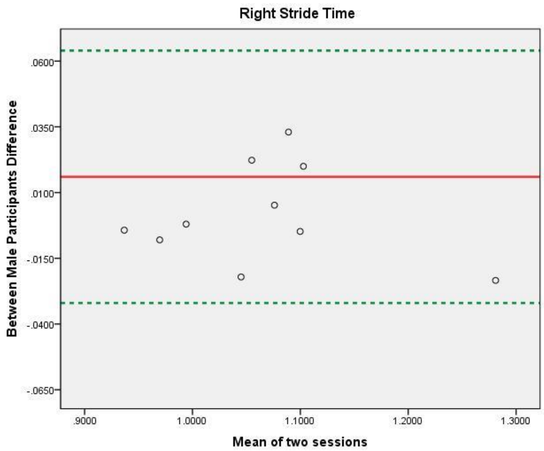
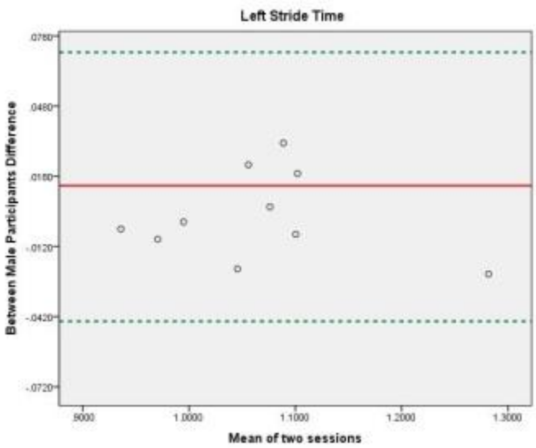
.0000
-.1000
-.2000
1.0000
1.2000
1.4000
1.6000
Mean of two sessions


Right Step Length
Between Male Participants Difference
.1000
.0000
-.1000
-.2000
.6000
.6500
.7000
.7500
.8000
.8500
Mean of two sessions


Left Step Length
Between Male Participants Difference
.0700
.0500
.0300
.0100
-.0100
-.0300
-.0500
-.0700
.5000
.6000
.7000
.8000
.9000
Mean of two sessions


Right Stride Time
Between Male Participants Difference
.0600
.0350
.0100
-.0150
-.0400
-.0650
.9000
1.0000
1.1000
1.2000
1.3000
Mean of two sessions


Left Stride Time
Between Male Participants Difference
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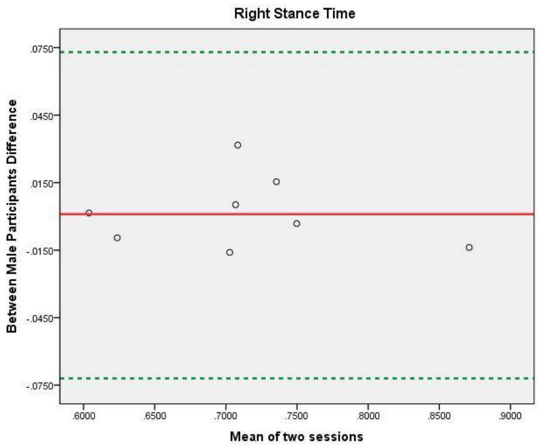
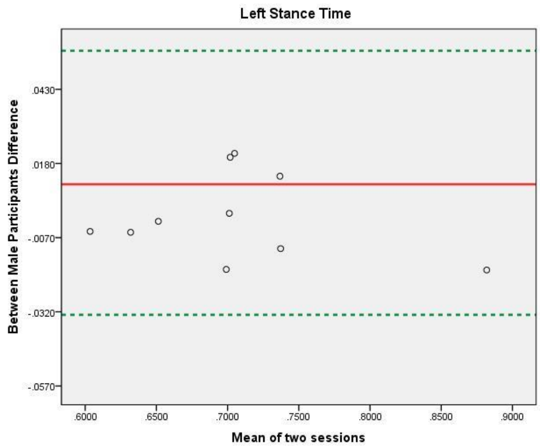
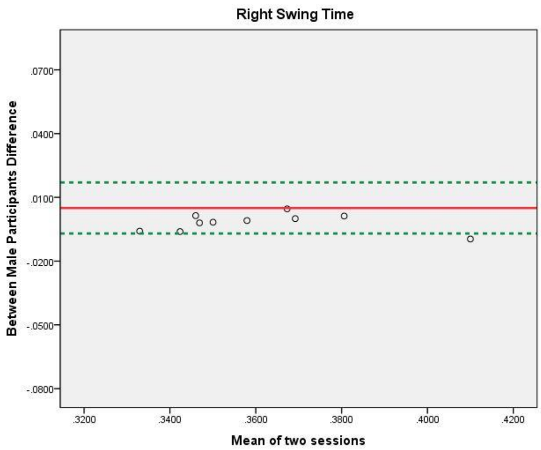
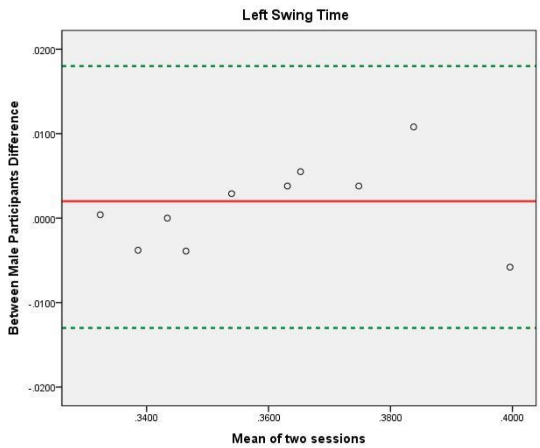
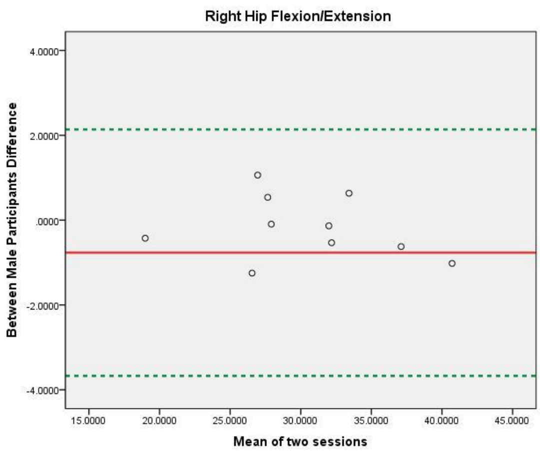
.0180
-.0120
-.0420
-.0720
.9000
1.0000
1.1000
1.2000
1.3000
Mean of two sessions

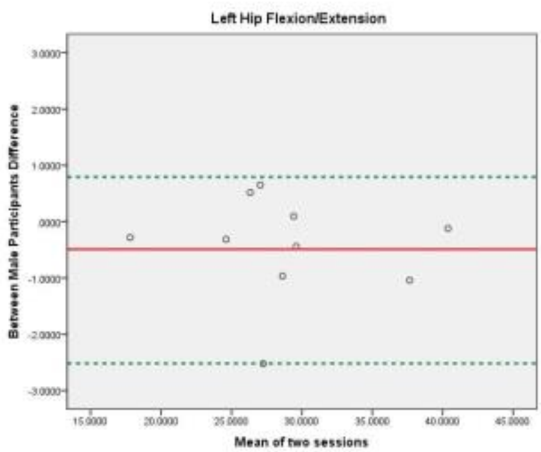

Right Stance Time
.0750
.0450
.0150
-.0150
-.0450
-.0750
Between Male Participants Difference
.6000
.6500
.7000
.7500
.8000
.8500
.9000
Mean of two sessions

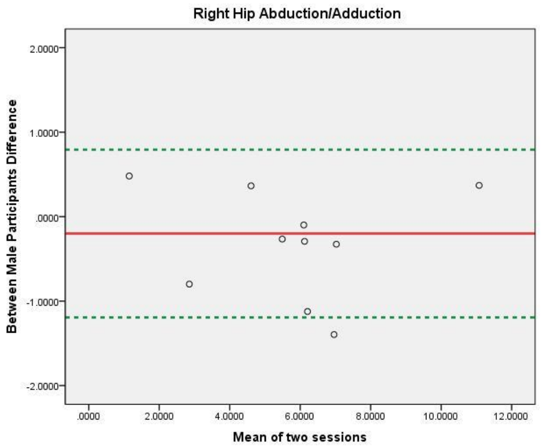

Left Stance Time
.0430
.0180
-.0070
-.0320
-.0570
Between Male Participants Difference
.6000
.6500
.7000
.7500
.8000
.8500
.9000
Mean of two sessions

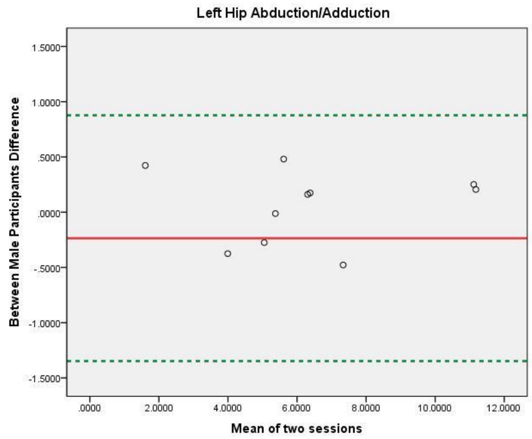

Right Swing Time
.0700
.0400
.0100
-.0200
-.0500
-.0800
Between Male Participants Difference
.3200
.3400
.3600
.3800
.4000
.4200
Mean of two sessions

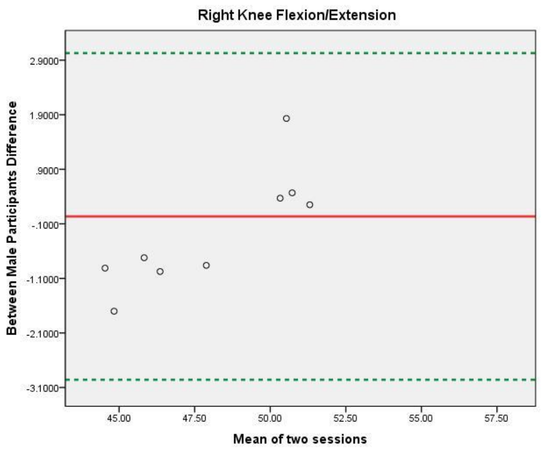

Left Swing Time
.0200
.0100
.0000
-.0100
-.0200
Between Male Participants Difference
.3400
.3600
.3800
.4000
Mean of two sessions

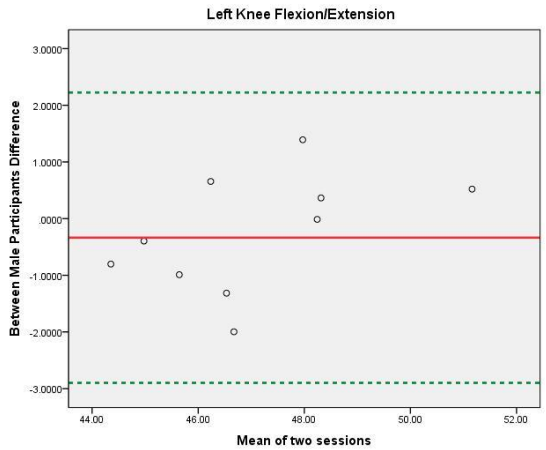

Right Hip Flexion/Extension
4.0000
2.0000
.0000
-2.0000
-4.0000
Between Male Participants Difference
15.0000
20.0000
25.0000
30.0000
35.0000
40.0000
45.0000
Mean of two sessions

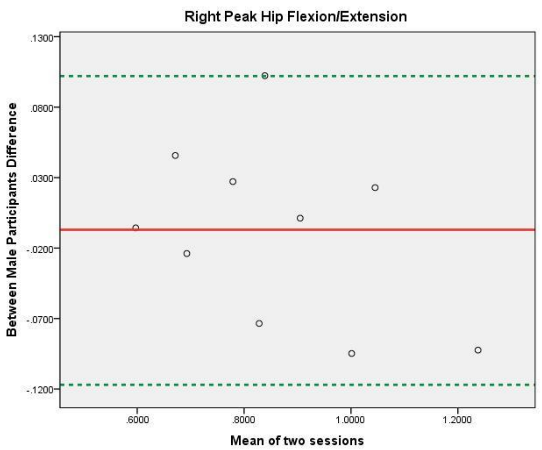

Left Hip Flexion/Extension
3.0000
2.0000
1.0000
.0000
-1.0000
-2.0000
-3.0000
Between Male Participants Difference
15.0000
20.0000
25.0000
30.0000
35.0000
40.0000
45.0000
Mean of two sessions

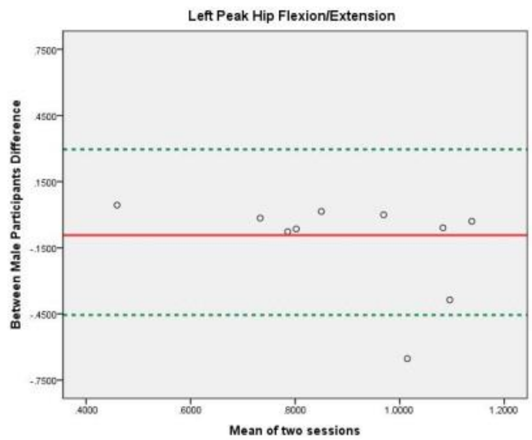

Right Hip Abduction/Adduction
Between Male Participants Difference
Mean of two sessions


Left Hip Abduction/Adduction
Between Male Participants Difference
Mean of two sessions


Right Knee Flexion/Extension
Between Male Participants Difference
Mean of two sessions


Left Knee Flexion/Extension
Between Male Participants Difference
Mean of two sessions


Right Peak Hip Flexion/Extension
Between Male Participants Difference
Mean of two sessions


Left Peak Hip Flexion/Extension
Between Male Participants Difference
Mean of two sessions

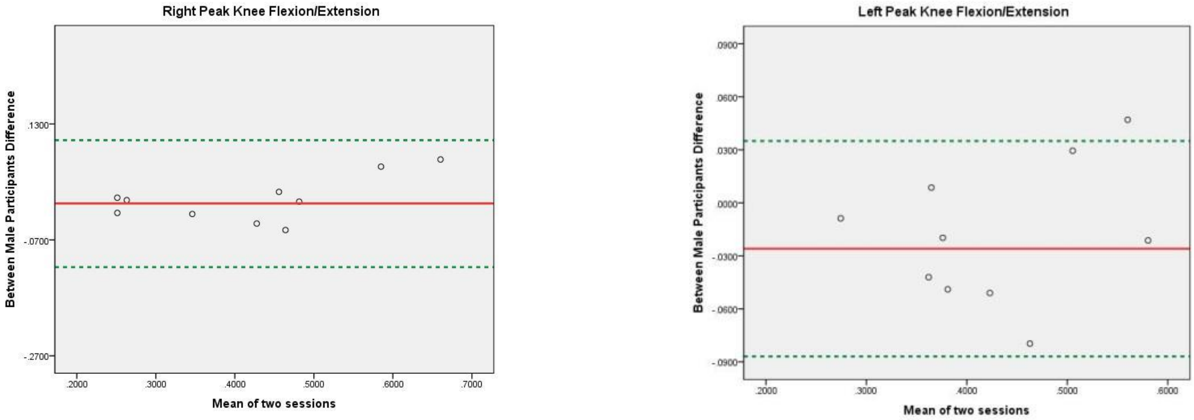


Figure 2: Bland-Altman plot for male and female groups for all of the gait parameters. Solid red line represents the mean difference between the two sessions, while upper and lower dashed lines represent the 95% limits of agreement.

Appendix 1

Human Body Model (HBM) lower-body marker

The information in this document is taken from the Motek 'HBM Reference Manual'.

Marker set:

In this study we have used the Human Body Model (HBM) lower-body marker set that consists of 25 markers (Table 1, Figure 1). 16 (which highlighted bold in Table 1 and green on the figure 1) of these markers are required for model initialization to define segment coordinate system and must be placed at precise anatomical landmarks. The other markers are needed for the inverse kinematic analysis (i.e. technical markers used to track motion of each segment) but it is not important to be accurately placed on the body.

Table 1: Markers used in the Human Body Model

Label	Anatomical location	Description
T10	T10	On the 10th thoracic vertebrae.
SACR	Sacrum bone	On the sacral bone.
NAVE	**Navel**	**On the navel.**
XYPH	**Xiphoid process**	**Xiphiod procces of the sternum.**
STRN	Sternum	On the jugular notch of the sternum.
LASIS	**Pelvic bone left front**	**Left anterior superior iliac spine**
RASIS	**Pelvic bone right front**	**Right anterior superior iliac spine**
LPSIS	Pelvic bone left back	Left posterior superior iliac spine
RPSIS	Pelvic bone right back	Right posterior superior iliac spine
LGTRO	**Left greater trochanter of the femur**	**On the center of the left greater trochanter**
FLTHI	Left thigh	On 1/3 on the line between the LGTRO and LLEK.
LLEK	**Left lateral epicondyle of the knee**	**On the lateral side of the joint axis**
LATI	Left anterior of the tibia	On 2/3 on the line between the LLEK and LLM.
LLM	**Left lateral malleolus of the ankle**	**The center of left lateral malleolus**
LHEE	**Left heel**	**Center of the heel at the same height as the toe**
LTOE	**Left toe**	**Tip of big toe**
LMT5	**Left 5th meta tarsal**	**Caput of the 5th meta tarsal bone, on joint line midfoot/toes**
RGTRO	**Right trochanter major of the femur**	**On the center of the right greater trochanter**
FRTHI	Right thigh	On 2/3 on the line between the RGTRO and RLEK.
RLEK	**Right lateral epicondyle of the knee**	**On the lateral side of the joint axis**
RATI	Right anterior of tibia	On 1/3 on the line between the RLEK and RLM.
RLM	**Right lateral malleolus of the ankle**	**The center of right lateral malleolus**
RHEE	**Right heel**	**Center of the heel at the same height as toe**
RTOE	**Right toe**	**Tip of big toe**
RMT5	**Right 5th meta tarsal**	**Caput of the 5th meta tarsal bone, on joint line midfoot/toes**

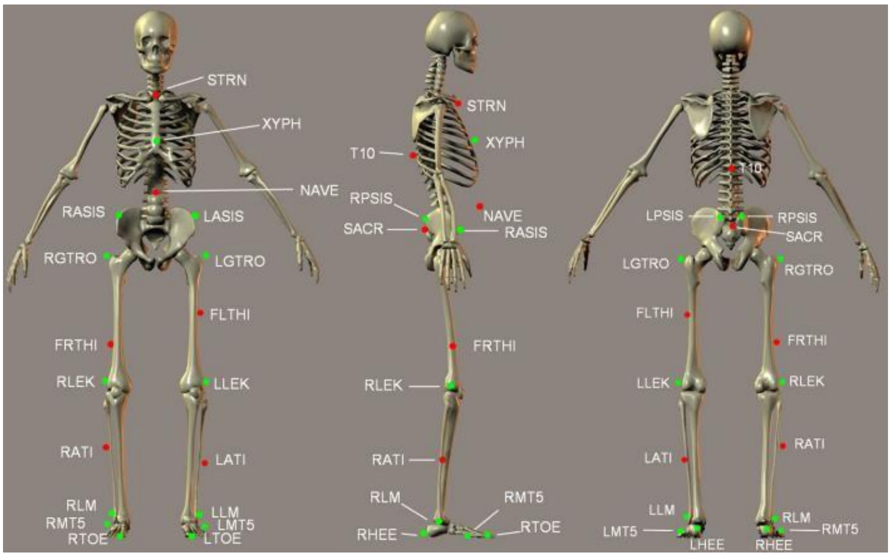


Figure 1. Diagram of markers