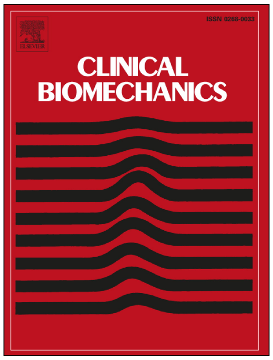

The implementation of inertial sensors for the assessment of temporal parameters of gait in the knee arthroplasty population

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Title: The implementation of inertial sensors for the assessment of temporal parameters of gait in the knee arthroplasty population

Author names and affiliations: Henri De Vroey[a,*], Filip Staes[b] , Ive Weygers[a] , Evie Vereecke[c], Jos Vanrenterghem[b], Jan Deklerck[a], Geert Van Damme[e], Hans Hallez[d], Kurt Claeys[a,b]

[a.]Department of Rehabilitation Sciences, KU Leuven Campus Bruges, Spoorwegstraat 12, 8200 Bruges, Belgium

[b.]Department of Rehabilitation Sciences, KU Leuven, Tervuursevest 101, 3001 Heverlee, Belgium

[c.]Department of Development and Regeneration, KULAK, Etienne Sabbelaan 53, 8500 Kortrijk, Belgium

[d.]Department of Computer Sciences, KU Leuven Campus Bruges, Spoorwegstraat 12, 8200 Bruges, Belgium

[e.]Department of Orthopaedic surgery, AZ Sint-Lucas, Sint-Lucaslaan 29, 8310 Bruges, Belgium

*** Corresponding author**:

Henri De Vroey
henri.devroey@kuleuven.be

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None

Abstract

Background: The use of inertial measurement units for the evaluation of temporal parameters of gait has been studied in many populations. However, currently no studies support the use of inertial measurement units for this purpose in the knee arthroplasty population. The objective of the present study was to investigate the agreement between an inertial measurement and camera based system for the assessment of temporal gait parameters in a knee arthroplasty population.

Methods: Sixteen knee arthroplasty patients performed 3 gait trials at a self-selected speed along a 6m walk-way. During the gait trials, gyroscope data from shank-worn inertial measurement units and motion data from optoelectronic cameras were collected simultaneously. A custom-made peak detection algorithm was used to identify gait events from gyroscope data, in order to compute cycle time, stance time and swing time. A marker and coordinate based algorithm was used to calculate temporal gait parameters from kinematical data derived from the camera system. Temporal variables were compared between both methods by calculating intra-class correlation coefficients, mean errors and root mean squared errors. Furthermore, Bland-Altman plots were constructed to assess the agreement between both methods.

Findings: Overall good to excellent intra-class correlation values (0.826-0.972) were found. Root mean squared errors between both methods ranged from 0.036 to 0.055s. High levels of agreement were observed for all variables.

Interpretation: These findings suggest that inertial measurement units can be used for outside laboratory assessment (e.g. in a hospital environment) of temporal gait parameters in the knee arthroplasty population.

Keywords: Temporal parameters, gait, inertial sensor, knee arthroplasty, validation, gyroscope

1. Introduction

Regaining normal walking has been identified as a key factor in the (early) rehabilitation after knee arthroplasty [1]. A well-established method for the evaluation of temporal gait features is the detection of gait events, such as toe off (TO) or initial contact (IC). The succession of these events enables the calculation of temporal gait parameters such as stance time, swing time, stride time and step time. Temporal variables are considered to have an important prognostic value when used within the context of risk of falling [2, 3] and the frailty syndrome [4] in the elderly population. However, their value remains to be investigated in rehabilitation after knee arthroplasty.

A kinematic and kinetic evaluation of gait mostly requires a dedicated laboratory equipped with a commonly found lab kit. However, these devices are expensive, complex to handle and data processing is often time consuming. To date, the gold standard to detect IC and TO events is force plate data based on ground reaction forces. However, recent studies comparing gait event detection from kinematic data with force plate data have demonstrated high levels of agreement between both methods, suggesting that the use of kinematic data for event detection is possible [5, 6]. During the past decade, new measurement systems such as wearable sensors or smartphone-based applications, have been developed that meet the clinical need for easier and outside-laboratory gait analysis [7, 8].

Inertial measurement units (IMUs) are small, lightweight sensors that comprise an accelerometer, gyroscope and magnetometer. These sensors are wireless and battery-powered, making them easy to attach to the body and monitor patients when moving freely for longer periods. IMUs can be used in environments where a standard camera-based motion capture system is no option, e.g. during an outdoor walking protocol or at the bedside of a hospitalized patient.

Previous research has confirmed the validity and reliability of IMUs to evaluate temporal gait parameters in other populations [9, 10]. Despite the fact that previous authors mainly used accelerometer data to analyze temporal gait features, there appears to be a growing interest in the use of gyroscope data for this purpose [11]. Considering that patients with a knee replacement show specific gait patterns (e.g. reduced knee range of motion and angular rotation rate during swing) [12, 13] it is important to test the accuracy of a gyroscope-based approach for the detection of gait phases in this population. Furthermore, the exponential increase in knee replacement procedures will ask for validated and easy to use instruments for the assessment of gait [14]. Therefore, the objective of this study is to assess the ability of an inertial measurement system to obtain reliable temporal gait parameters in the knee arthroplasty population. We hypothesize that temporal parameters based on event detection using IMUs will show high correlations with those derived from a camera based motion capture system.

2. Methods

2.1 Subjects

Sixteen knee arthroplasty patients (age: 64.1y, SD 7.48y; height: 1.70m, SD 0.10cm; weight: 91.3kg, SD 18.29kg) that were one year (1.2 years, SD 89.7 days) post knee replacement surgery participated in this study. Subjects filled out the Dutch version of the Oxford 12-item Knee Score(OKS), to assess functionality and pain levels experienced when performing activities of daily living [15]. The subject characteristics and OKS-scores are presented in table 1. Exclusion criteria for this study were any comorbidity affecting gait such as structural deformities, other trauma to the lower limbs, medication and neurological or systemic diseases. All subjects gave their written informed consent and the Medical Research Ethics Committee of KU Leuven with respect to the declaration of Helsinki approved all test procedures.

insert table 1 here

2.2 Data collection

Data were collected for each subject as they walked barefoot in a straight line along a 6-m-long walk way. Each subject performed three walking trials at a self-selected speed, providing one or two full gait cycles per trial depending on marker visibility within the motion capture volume.

Data from IMUs were collected at a sampling rate of 100Hz using Xsens MTw sensors (Enschede, The Netherlands). Each subject was fitted with an IMU at the left and right lower leg which was rigidly secured to the anteromedial facet of the tibia, at approximately 5cm below the knee joint, using double-sided adhesive tape and therapeutic tape. Data from the sensors included time-synchronized accelerometer and gyroscope measurements, but in this study only gyroscope measurements were used for data analysis.

kinematic data were recorded at a frequency of 120 Hz using a six-camera Optitrack flex 13 (NaturalPoint, Corvalis, USA) optoelectronic system. A standardized calibration procedure was done before each test session. Marker trajectory residuals were always in the excellent range. Reflective markers (n= 44) were positioned by an experienced physiotherapist according to the lower limb and trunk model [16, 17] to the 7th cervical and, 8th thoracic vertebrae, incisura jugularis, xiphoidal process, left and right acromion, PSIS, anterior superior iliac spine, Iliac crest, trochanter major, medial femoral epicondyle, lateral femoral epicondyle, lateral malleolus, medial malleolus, the first and fifth metatarsal head and both heels. Tracking markers (16) were rigidly secured to the anterolateral aspect of both thighs (8) and shanks (8).

IMU and motion capture data were recorded simultaneously and synchronized in time, based on the first gait event detected within the capture volume. Gait phases from corresponding strides were identified, allowing for the comparison of resulting gait phase durations.

2.3 Data processing

Raw gyroscope data about the z-axis were extracted from the shank worn IMU and showed a recurrent and very distinctive pattern, consisting of a set of high positive angular velocity readings that were followed by a number of negative peaks (fig. 1.). The signal was filtered using a low pass finite impulse response filter, with a stop-band attenuation of 60dB to ensure a strict suppression of frequencies that were higher than the cutoff frequency, which was set at 6Hz. A zero-phase filter implementation was also used ensuring that the filtered signal size never exceeded the size of the original signal. Afterwards a normalization between -1 and 1 was performed based on the signals maximal values. A find peak function was implemented in Matlab version R2016a (Mathworks, USA) in order to assess timing of IC and TO. Both gait events were identified based on a local maximum principle, which defines a local maximum as a data sample that is larger than the two neighboring samples. First, a minimal peak height of -0.1 was defined based on the normalization parameters. Second, a minimal between-peak distance threshold was set based on the subject’s speed, considering a minimum duration of 0.5 seconds between two consecutive ICs. This threshold also aimed to clear out any possible aberrant peaks occurring within a gait cycle. The first negative peak before crossing the zero-line was defined as a TO. An additional filtering of the peaks was carried out based on the logical IC and TO sequence (e.g. every detection starts with a TO and is followed by an IC), enabling the computation of relevant gait phases.

Kinematic data were also filtered using a low pass Butterworth filter, with a cutoff frequency set at 6Hz. TO and IC events identified from kinematic data were automatically derived using a previously validated coordinate- and marker-based algorithm respectively [18, 19]. All trials and kinematic event detections were visually inspected using Visual 3D v5 software (v5.02.30, C-motion, Germantown USA). Following temporal gait parameters were assessed at the operated and non-operated leg: cycle time (CyT), stance time (StT) and swing time (SwT). CyT was defined as the time between IC of one foot and the following IC of the same foot, StT was defined as the time between IC of one foot and the following TO of the same foot and SwT was defined as the time between TO at one side until following IC at the same side.

Insert fig. 1 here

Synchronization of motion capture and inertial data was performed using Matlab (R2016a, Natick, MA) by adjusting time differences between IC derived from the IMU system and the first corresponding IC that fell within the capture volume of the camera system. IC detected by means of raw sensor gyroscopic data was time-matched to within 0.01s of the corresponding IC detected by the motion capture system.

2.4 Statistical analysis

Kinematic data from the Optitrack system was used as a gold standard in this study. The correlation between the IMU and camera based system for the aforementioned variables was evaluated using intra-class correlation coefficients (ICC). ICCs and their 95% confidence intervals were calculated using a mixed two-way analysis for absolute agreement with a test value=0 and alfa=0.05. ICCs were rated as excellent (0.91-1), good (0.74-0.9), moderate (0.4-0.73) and poor (0-0.39) [20]. Mean difference, standard deviations and Root mean square differences were calculated.

Serfontein and Jaroszewicz demonstrated that despite the fact that two measurement methods show high correlations, they could potentially conceal a poor agreement [21]. This is why the agreement between the two methods was assessed by calculating the proportional bias (mean difference between both measurement systems) and limits of agreement (LOA) (1.96*standard deviation of the difference between both systems) and are presented as Bland-Altman plots. All statistical tests were conducted in SPSS (version24, IBM corp, Armonk, NY).

3. Results

Overall, good to excellent correlations were demonstrated between both measurement techniques for the different temporal variables as shown in Table 2. For CyT, excellent ICCs of 0.979 and 0.972 were found, both at the operated and non-operated leg, respectively. A small bias of -0.018s (operated) and 0.006s (non-operated) was observed. Excellent ICCs of 0.953 and 0.913 could also be demonstrated for StT, at the operated and non-operated leg, respectively. However, a slightly higher bias of 0.041s was found when evaluating StT at the non-operated leg. A good ICC of 0.826 was found for the SwT at the operated leg, which was in contrast to the non-operated leg, showing an excellent ICC of 0.917.

***Insert table 2 here ***

Bland-Altman plots were constructed to evaluate the agreement between both methods (fig. 2). For CyT at the operated leg LOA's were found ranging up to ±0.088s. Slightly higher LOA of ±0.102s were found when evaluating the non-operated leg. Similarly to the CyT the LOA found for StT and SwT were situated between ±0.086s and ±0.096s.

***Insert figure 2 here ***

4. Discussion

The key finding of this study is a strong agreement and excellent correlations between temporal parameters of gait evaluated by means of a camera based motion capture system and those derived from gyroscopic data collected through shank worn IMUs. The lowest correlation was observed for SwT, which still demonstrated a good correlation of 0.826. A possible explanation for this lower correlation could be attributed to a greater variability in TO detection using the algorithm proposed by Zeni et al., who reported that up to 25% of TO detections were within 2 frames from the actual kinetic detection, likely a consequence of flexion-extension in the metatarsal-phalangeal joints. A study comparing multiple algorithms for the detection of gait events from kinematic data, demonstrated small errors in timing estimation (±0.08s) of TO events compared to kinetic data obtained by means of force plates [22]. Thus, the use of a different algorithm may lead to slightly different, but clinically non-significant, results. Furthermore, since swing only accounts for roughly 40% of the stride time, a shorter time period is needed to complete this phase of the gait cycle, resulting in proportionally bigger RMSE and thus lower ICC values.

Nevertheless, findings reported in this study suggest that IMUs can be used for the assessment of temporal gait parameters in the knee arthroplasty population since our results are in accordance with findings reported in similar studies performed in other populations [9, 10].

The influence of sensor placement (foot, waist, trunk, shank) has been discussed in previous literature, and appears to be critical for the detection of temporal gait events [23, 24]. In the current study sensors were mounted to the anteromedial facet of the tibia just below the knee to reduce the chance of soft-tissue artefacts. This sensor placement was in contrast with other studies where sensors were mounted on the foot or waist [25]. Though, previous authors stated that one should be careful when interpreting gait data from a single IMU attached to the pelvis, as this method showed missed gait events. Secondly, gyroscopic data from shank worn IMUs shows a clear and distinctive pattern, which enables an easy identification of IC and TO events (fig. 1).

The outcome of temporal parameters of gait is an important measure used for the diagnosis and evaluation of several functional conditions, such as the risk of falling, cognitive decline, gait quality and the frailty syndrome in the elderly [2, 4, 26, 27].Therefore, the excellent agreement levels and high reliability found in this study suggest that IMUs can also be used in the knee arthroplasty population for the assessment of temporal gait parameters. These findings may become important in the clinical evaluation of knee arthroplasty patients, as the use of IMUs has been reported to have many advantages compared to standard gait analysis. Their portability, small size and user-friendliness make them useful for settings (e.g. in a private practice or home environment) where the use of a standard camera based system might not be possible, making the evaluation of patients in for example an outdoor gait protocol possible. Furthermore, the spatial restrictions of a standard laboratory become clear when assessing stability measures and variability in gait, which need a greater amount of strides to overcome a much discussed reliability problem [28, 29]. In addition, experience in our lab has shown that the use of IMUs dramatically reduces the time needed to perform data collection and processing. For instance in this study, the placement of markers would take on average 20 min, whereas the mounting of sensors only took 3 min. Correcting marker trajectories, gap filling, filtering and computing gait events from kinematic data lasted at least for about 40 min per subject/trial (~20h total). Computing gait events from IMU data, using the proposed algorithm, only took 10 min per subject/trial (~5h total). Yet, future research will need to be conducted outside a laboratory in order to prove IMUs are purported to be most useful.

Some limitations should be taken into account when interpreting the results of the current study. Knee replacement subjects in this study presented fairly high OKS scores, suggesting a good functionality and less impairment. However, a Pearson’s correlation test could not demonstrate any significant correlations between functionality scores and the measurement errors for temporal gait parameters. Furthermore, the subjects demonstrated rather slow gait speeds which might also influence the accuracy of the present methodology. Again, no significant relation could be found between gait speed and measurement error. Filtering parameters and sampling frequency were set ad hoc, in order to justify the use of certain filtering and sampling frequencies, future studies should investigate their influence on the resulting temporal gait parameters. At last, the interpretation of the magnitude of ICCs is always open for debate, and we have chosen one commonly used scale [20]. Whereas this scale is a useful guideline, and in fact quite a conservative one compared to some others, the full interpretation of whether one would accept one or another measurement for clinical practice is a much more complex issue, depending on principles of diagnostic and/or prognostics, as well as clinical significance.

5. Conclusions

Although the use of inertial sensors had been validated for the assessment of temporal parameters of gait in different (healthy and pathologic) populations, this was the first study to investigate their use in a knee arthroplasty population. High ICCs and good to excellent levels of agreement were found when comparing temporal parameters derived from gyroscopic data extracted from shank worn inertial sensors and those from a camera based motion capture system. These findings indicate that IMUs can be used as a reliable tool for the evaluation of temporal parameters of gait in the knee arthroplasty population.

Acknowledgements

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Conflict of interest statement

Authors declare that there were no conflicts of interest

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Fig. 1. Shank angular rate, showing distinctive peaks at initial contact and toe-off
🟡 = Initial Contact is characterized by a negative peak (1),(4) following a large positive angular rate (3). 🔻 = Toe Off, which is characterized by the negative peak preceding the large positive angular rate (3) produced by the revolution of the shank during swing. (+) indicate a positive revolution of the shank. (-) indicate a negative revolution of the shank

Fig. 2. Bland-Altman plots comparing results from the inertial measurement units and camera based system for the Cycle time, Stance time and Swing time at the operated and non-operated leg.
Bias -·-· , limits of agreement ----- are shown for each variable

Table 1
Patient characteristics

	Subjects (n=16)	
	Mean	*SD*
Gender	8M/8F	/
Age (years)	64.69	±7.48
Height (m)	1.68	±0.10
Mass (kg)	89.86	±18.29
BMI (kg/m^2)	31.83	±6.01
Age of prosthesis (days)	454.86	±89.67
OKS score	42.6	±5.06

M: Male; F: Female; SD: standard deviation; BMI: Body Mass Index; OKS: Oxford 12-item Knee Score

Table 2

ICC-Coefficients and 95% confidence intervals, Mean differences and Root Mean Square differences for temporal variables between the camera-based and IMU system.

	ICC (95% CI)	Mean Camera(s)	Mean IMU(s)	Mean difference (s)	*SD (s)*	*RMSE (s)*
CyT *op*	0.979 (0.952 – 0.991)	1.252	1.269	-0.018	±0.045	0.036
CyT *non-op*	0.972 (0.939 – 0.987)	1.252	1.246	0.006	±0.052	0.041
StT op	0.953 (0.862 – 0.981)	0.748	0.722	0.026	±0.044	0.041
StT non-op	0.913 (0.517 – 0.972)	0.754	0.713	0.041	±0.044	0.054
SwT op	0.826 (0.445 – 0.932)	0.504	0.593	-0.034	±0.047	0.049
SwT non-op	0.917 (0.821 – 0.962)	0.504	0.533	-0.029	±0.049	0.055

Cyt: cycle time; StT: stance time; SwT: swing time; op: operated leg; non-op: non-operated leg; ICC: intra-class correlation coefficient (95% confidence interval); SD: standard deviation; RMS: root mean square

Highlights

- There is a need for extra-laboratory gait analysis of patients with knee arthroplasty
- Temporal gait parameters from wearable sensors and a camera system were compared
- High correlations were demonstrated between both measurement systems
- Wearable sensors can be used for the assessment of temporal gait parameters

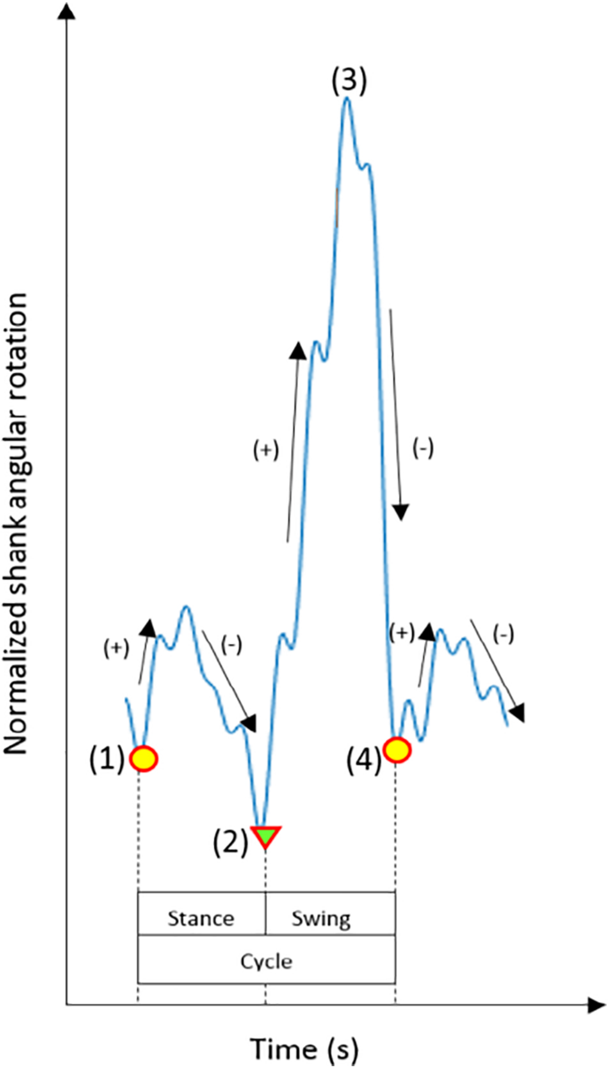
Normalized shank angular rotation
(3)
(+)
(-)
(+)
(-)
(+)
(-)
(1)
(2)
(4)
Stance
Swing
Cycle
Time (s)

Figure 1

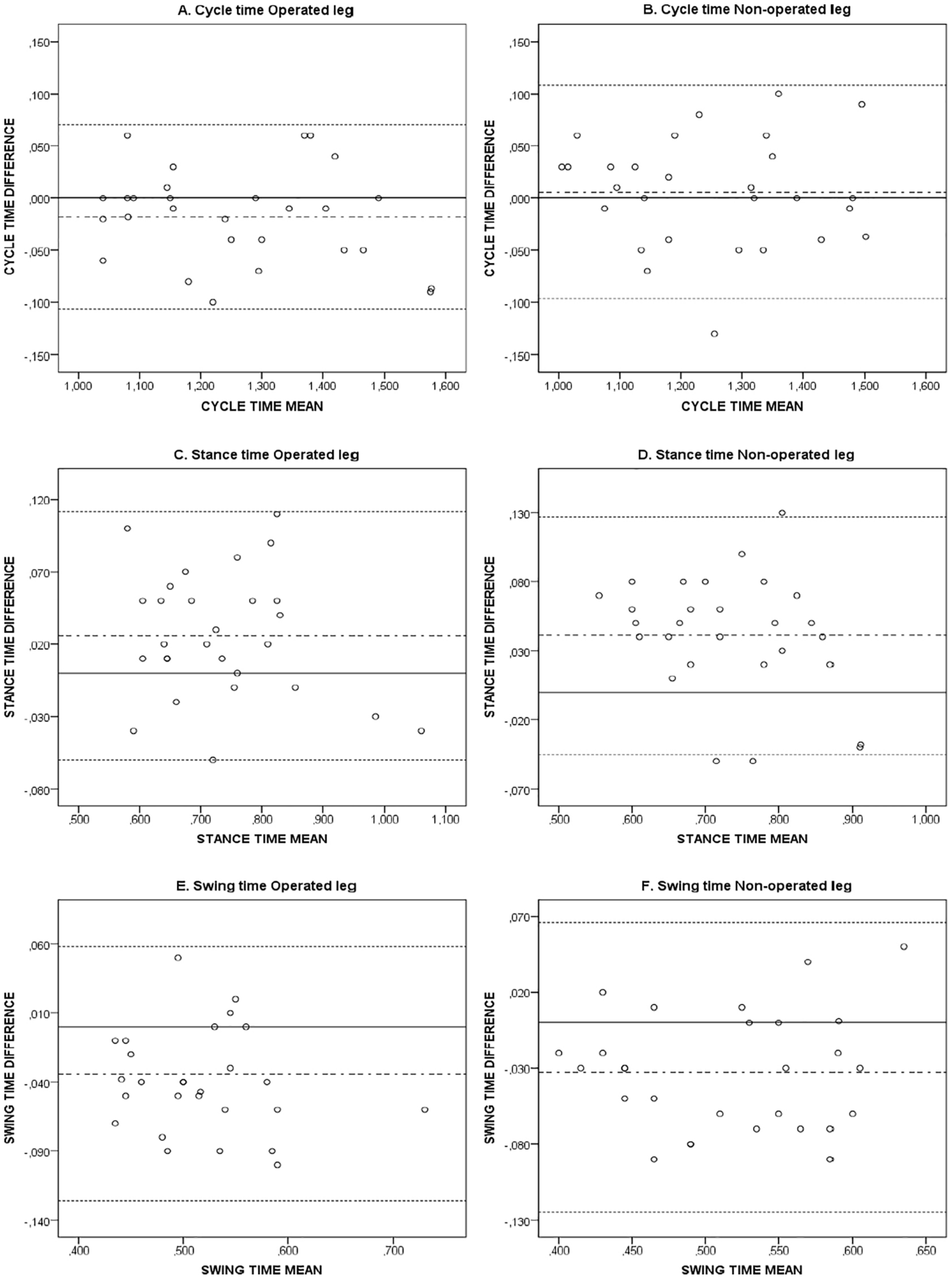
A. Cycle time Operated leg
B. Cycle time Non-operated leg
CYCLE TIME DIFFERENCE
CYCLE TIME MEAN
,150
,100
,050
,000
-,050
-,100
-,150
1,000
1,100
1,200
1,300
1,400
1,500
1,600
C. Stance time Operated leg
D. Stance time Non-operated leg
STANCE TIME DIFFERENCE
STANCE TIME MEAN
,120
,070
,020
-,030
-,080
,130
,080
,030
-,020
-,070
,500
,600
,700
,800
,900
1,000
1,100
E. Swing time Operated leg
F. Swing time Non-operated leg
SWING TIME DIFFERENCE
SWING TIME MEAN
,060
,010
-,040
-,090
-,140
,070
,020
-,030
-,080
-,130
,400
,450
,500
,550
,600
,650
,700

Figure 2