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SPORTS & EXERCISE | RESEARCH ARTICLE

Concurrent validity and repeatability of inertial sensor gait analysis system for the measurement of gait parameters of young healthy adults

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Abstract: Purpose: To examine the concurrent validity and test–retest repeatability of the RehaWatch® system for the assessment of spatiotemporal parameters of gait.

Methods: Spatiotemporal gait parameters were recorded using the RehaWatch® and GAITRite® systems among 17 healthy young adults (mean age = 21.5 years, SD = 1.9). Concurrent validity was assessed by comparing data obtained using both gait measurement systems, and repeatability of the RehaWatch® measurements was assessed between the six measurement trials.

Results: The level of agreement between both measurement systems was strong as for the velocity, cadence, and double support time of the left side (r = 0.73–0.95) and moderate for double support time of the right side, and swing and stance time of both sides (r = 0.46–0.69). The hierarchical linear mixed model showed mostly good repeatability for gait parameters between the six trials. Despite some

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Combining specializations in biomechanics, gait analysis and rehabilitation, the authors have collaborated on measures related to quantifying movement and performance of the healthy people and patients with different musculoskeletal and neurological pathologies.

PUBLIC INTEREST STATEMENT

This research examined the validity and the repeatability of the RehaWatch® gait analysis system. Gait analysis is an important tool for health professionals to identify walking difficulties or effectiveness of treatment interventions. RehaWatch® is a body-worn inertial sensor system providing a possibility to simulate walking outside a laboratory setting. The knowledge concerning the validity and repeatability of RehaWatch® system is scarce. Concurrent validity of RehaWatch® can be established when concurrent measurements are verified to meet measurements of the GAITRite® walkway system. The repeatability of the RehaWatch® is essential to ensure that any difference in measurements between testing sessions reflects actual differences or changes, rather than a random or systematic error in the measurement technique. The study found that the RehaWatch® has acceptable validity and repeatability in most of the gait parameters in healthy young adults. Research is needed on the psychometric properties in subjects with different diseases and gait disorders.

statistically significant mean differences over the trials, such as in cadence and swing time of left side, the differences were minor had no clinical significance.
Conclusions: The RehaWatch® system has acceptable validity and test–retest repeatability in most of the spatiotemporal gait parameters in healthy young adults. The RehaWatch® system could be recommended to be used consistently and carefully for both clinical and research purposes.

Subjects: Medical Devices; Technology; Medical Technology & Engineering; Joint Replacement; Sports Medicine; Prosthetics & Orthotics

Keywords: gait; spatiotemporal parameters; measurement; validity; repeatability

1. Introduction

The objective measurement of gait parameters in the clinical and research settings requires valid and reliable measurement methods. Gait analysis systems, such as camera-based three-dimensional motion analyses and force plates systems, can provide useful and accurate information for evaluating gait disorders, the effect of therapeutic interventions and for treatment planning. Despite of the high accuracy, most of these advanced systems are expensive, time-consuming and labour-intensive, being unusable in certain contexts, such as in outdoor use and in normal daily activities. Moreover, many of the methods measure only a limited number of steps, which is not enough when simulating the normal walking patterns (Galna, Lord, & Rochester, 2013). The gold-standard GAITRite® is a portable walkway system that calculates spatio-temporal gait parameters, such as cadence, step length, stance time, swing time, and double support time using a pressure sensor mat. The method has been used extensively in research and clinically with various ages and populations due to its ease of use and established validity (Bilney, Morris & Webster, 2003; Cutlip, Mancinelli, & Huber, 2000; McDonough, Batavia, & Chen, 2001; Webster, Wittwer, & Feller, 2005) and reliability (Cjt & Besser, 2004; Kuys, Braue, & Ada, 2011; Menz, Latt, & Tiedemann, 2004; Wittwer, Webster, & Andrews, 2008). In recent years, low-cost and highly portable footswitches systems and inertial sensor-based methods (Beauchet, Hermann, & Grandjean, 2008; Muro-de-la-Herran, García-Zapirain, & Méndez-Zorrilla, 2014; Yang & Li, 2012) have also become increasingly used in gait analyses complementing GAITRite. Among those, the user-friendly, inertial sensor-based gait analysis system RehaWatch® provides a possibility to simulate natural, continuous walking when a large number of steps are needed. As a portable and body-worn sensor system RehaWatch® can be used outside a laboratory setting enabling gait data collection within less than 10 min. The system comprises multidirectional accelerometers, gyroscopes and magnetometers and software computing spatiotemporal gait parameters during walking. However, to date the knowledge concerning the validity and repeatability of RehaWatch® assessed during natural gait environment is scarce (Schwesig, Kauert, & Wust, 2010; Schwesig, Lechte, & Fischer, 2011). This information is critical for its potential application in research and clinical practice.

The overall object of our study was to examine the gait parameters with both the GAITRite® walkway and RehaWatch® in healthy and hip-operated adults. However, as a first step, we needed to determine the agreement of the measurement results between GAITRite® and RehaWatch® and also the repeatability of the measurements with RehaWatch®. The aim of this study was to examine the concurrent validity of the RehaWatch® versus the GAITRite® walkway for the measurement of spatiotemporal gait parameters in healthy young adults. Moreover, the intra-tester repeatability of RehaWatch® in measuring spatiotemporal gait parameters was determined.

2. Methods

2.1. Subjects

Seventeen young and healthy adults (14 women, 3 men, mean age 21.5 (SD 1.2)) years, mean height 1.7 (SD 0.1) m, mean weight 68.4 (SD 11.6) kg, mean body mass index 23.5 (SD 2.3) were

recruited from the students of the Turku University of Applied Sciences. Voluntary subjects were free from any neurological, cardiovascular, or musculoskeletal disorders, and had no walking difficulties at the time of testing. The study was conducted after obtaining approval from the ethics committee of Turku University Hospital. All subjects provided their written informed consent as per the declaration of Helsinki 1964.

2.2. Equipment

GAITRite® (Cutlip et al., 2000) is an electronic walkway utilized to measure gait parameters of its pressure activated sensors (500 cm, 89 cm, 0.625 cm, 13,824 pressure sensors spaced at intervals of 1.27 cm, sample frequency 80 Hz, resolution 12,5 ms, CIR System, Inc., NY, USA, 2007). The system is connected to a computer via an interface cable and requires no separate electrodes or devices to be attached to the subject. When subjects walk on the carpet, the series of sensors on the carpet are activated by mechanical pressure of the foot. The data from the activated sensors are collected by on-board processors and transferred to the computer through a serial port. The device records the time and position of the foot falls on the carpet automatically. This information is converted by the software algorithms into spatial and temporal gait parameters. Data saved on the computer was analyzed using GAITRite® Version 3.4. The measurement carpet was positioned in the middle of the 15 m walkway. The subject began to walk from the marked area from the beginning of the walkway and ended the walk to the marked area at the end of the walkway.

RehaWatch® (Schwesig et al., 2010, 2011) is an inertial sensor-based gait analysis system (ISGAS) (RehaWatch®-system; HASOMED® GmbH, Germany) with measurement sensors attached to the lateral ankle using a special device (Figure 1). Each sensor contains three accelerometers and three gyroscopes (Analog Devices, Norwood, MA, USA) measuring foot motion in six degrees of freedom. The measurement range of the accelerometers is ± 5 g and gyroscopes ± 600°/s. The sampling rate is 512 Hz. Gait measurements are performed in offline mode. The primary gait event is heel-strike and all other gait events are identified relative to heel-strike. Spatiotemporal gait parameters and gait phases are calculated automatically.

The measurement system consists of a mobile computer (DataLogger) attached to the patient using straps. The internal memory of the inertial sensors allows continuous data storage and the data of the sensors are received via cable-connection and stored in the DataLogger. At the end of the walking measurement the data is transferred from the DataLogger to the PC using an USB-stick. The measured data includes accelerations and angular velocities for the calculations of the spatio-temporal parameters. Angular velocities were integrated to obtain information on the spatial orientation of the sensor.

2.3. Measurement protocol

The walking analysis with RehaWatch® was measured at a 15-m walkway, which was the same walkway when walking over the GAITRite® mat. When measuring with both measurement

Figure 1. The RehaWatch® system with the sensors on the lateral side of the shoes.

systems, the subjects wore standardized foot wears, which were solid flat low shoes or sport shoes (heel < 2 cm). Before data collection the subjects were asked to practice at their self-selected walking speed over the mat in order to familiarize themselves with the test procedure. To standardize the walking pace with both measurement devices the rhythm of the self-selected and comfortable walking speed was settled to the metronome for the final measurements. In the final measurements of both systems the subjects walked at the same preferred walking pace standardized with metronome (beats/min). Each subject performed six individual walking trials simultaneously with both measurement devices in the same session. The same experienced physical therapist performed all measurements.

The spatiotemporal gait parameters measured and analyzed with both devices were walking velocity (cm/s), swing time of left and right side (%), stance time of left and right side (%), double support time of left and right side (%), and cadence (steps/min). Average values (mean) of the all gait parameters were calculated over the six trials (Figure 2).

2.4. Statistical analysis

The results are presented as means and standard deviations (SD) of the measurements. The paired *t*-test was used to determine systematic differences between the gait parameters obtained using the two measurement systems. Pearson product-moment correlation coefficient (*r*) of method errors with 95% confidence intervals (CI) was calculated for the absolute comparison of parameters obtained using the two systems.

The test–retest repeatability of gait parameters measured using RehaWatch® was analyzed with hierarchical linear mixed model testing whether there are differences between the six different trials. The SAS® Version 9.4 for Windows was used in the statistical analysis. A significance level 0.05 (two-tailed) was considered as statistically significance.

3. Results

When analyzing the overall agreement of the spatiotemporal gait parameters between two measurement systems the results (means over six trials) show that all the gait parameters were significantly different, except cadence. The mean and SD of the spatiotemporal gait parameters are presented in Table 1. Velocity was higher and swing time of both sides was longer, whereas double support and stance time of both sides were shorter in RehaWatch®.

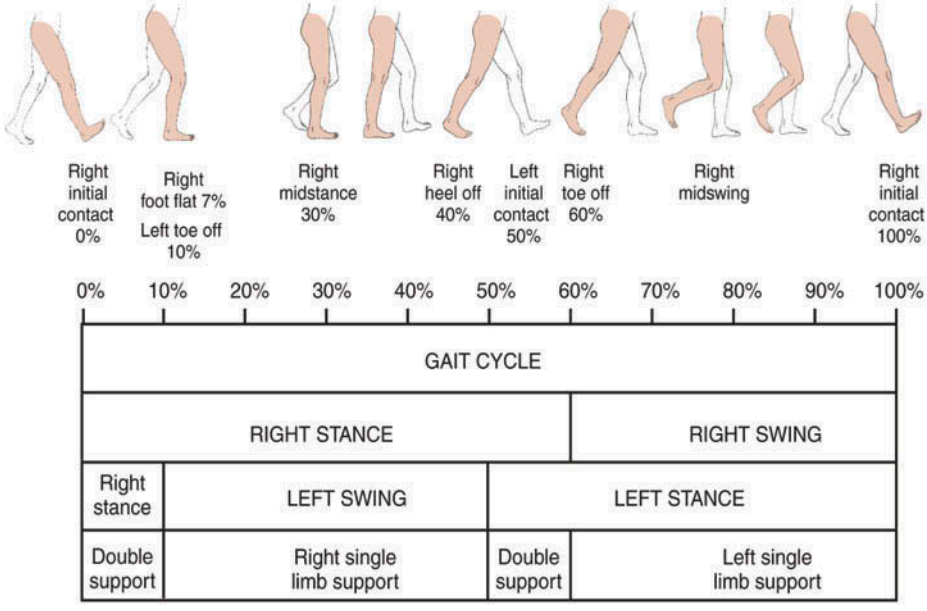

Figure 2. Schematic representation of the measured gait parameters (Levangie & Norkin 2011).

Table 1. Mean (SD) of spatiotemporal gait parameters of subjects and concurrent validity measured with GAITrite® and RehaWatch-system®

Gait parameters	GAITrite® Mean (SD)	RehaWatch® Mean (SD)	Pearson CC (*r*) 95%CI Mean (SD)	Mean difference between two Measurement instruments (95% CI)
Velocity (cm/s)	154 .27 (9.46)	158 .37 (7.93)	0.89 (0.73–0.96)	−4. 10 (−6.30, −1.91)***
Cadence (steps/min)	117 .78 (5.72)	117 .74 (5.96)	0.95 (0.87–0.98)	0. 04 (−0.91, 0.99)
Double support left (%GC)	19 .97 (2.00)	17 .02 (2.61)	0.73 (0.39–0.90)	2. 95 (2.03, 3.65)***
Double support right (%GC)	19 .87 (1.88)	17 .02 (2.62)	0.69 (0.32–0.88)	2. 84 (1.87, 3.81)***
Swing time left (%GC)	40 .22 (0.90)	41 .40 (1.37)	0.67 (0.28–0.87)	−1. 18 (−1.71, −0.66)***
Swing time right (%GC)	40 .32 (1.37)	41 .61 (1.41)	0.46 (−0.03–0.77)	−1. 29 (−2.04, −0.55)*
Stance left (%GC)	59 .78 (0.92)	58 .43 (1.41)	0.64 (0.23–0.86)	1. 35 (0.79, 1.91)***
Stance right (%GC)	59 .69 (1.38)	58 .44 (1.43)	0.59 (0.16–0.84)	1. 26 (0.60, 1.90)***

Pearson CC (*r*), Pearson correlation coefficient; 95% CI, 95% confidence interval; %GC, percent from the gait cycle.
*$p < 0.05$, ***$p \leq 0.001$.

However, despite differences of the mean measurement values the concurrent validity between the two measurement systems was acceptable with correlation coefficients (*r*) within the range of 0.46–0.95. The agreement of the measurements between two systems was strong as for the velocity, cadence, and double support time of left side with the correlation coefficient (*r*) ranging from 0.73 to 0.95 or moderate for double support time of right side and swing and stance time of both sides with the correlation coefficients (*r*) between 0.46 and 0.69.

The assessment of repeatability of spatiotemporal gait parameters over the six separate trials obtained by RehaWatch® show no statistically significant differences between the measurement trials, except cadence ($p = 0.03$) and swing time of left side ($p = 0.03$) (Table 2). However, the differences between trials were extremely minor in all gait parameters. The standard errors (SE) of all gait parameters were similar in all six measurement trials.

When the differences of gait parameters between separate measurement trials were analyzed in detail there were statistically significant differences ($p < 0.05$) between measurements in velocity, double support time of both sides, swing and stance time of left side, and in cadence. In velocity there were differences between trials 2 and 5 (difference −5.8 cm/s, $p = 0.013$), 3 and 5 (difference −6.1 cm/s, $p = 0.009$), and also 4 and 5 (−5.5 cm/s, $p = 0.019$). In double support time of both left and right side the differences existed between trials 1 and 6 (−1.2%, left and left side $p = 0.013$) and in swing time of left side between trials 1 and 2 (0.7%, $p = 0.010$), 1 and 5 (0.7%, $p = 0.012$), and 1 and 6 (0.8 %, $p = 0.003$). In stance time of left side the differences were found between trials 1 and 5 (−0.6%, $p = 0.039$) and in cadence between measurement trials 1 and 6 (−0.9 steps/min, $p = 0.018$), 3 and 6 (−1.0 steps/min, $p = 0.009$) and between 4 and 6 (−0.8 steps/min, $p = 0.041$).

4. Discussion

This study was conducted to examine the concurrent validity of the RehaWatch® system with GAITRite® and the test–retest reliability of RehaWatch® with healthy young adults. There was strong validity for velocity, cadence and double support time of the left side, moderate validity for double support time of the right side and swing and stance time of both sides between RehaWatch® and GAITRite®. Low mean differences between six trials showed mostly good repeatability of the RehaWatch® system.

Table 2. Test–retest repeatability between six measurement trials with RehaWatch®-system presented as means (SE)

Gait parameters	Trial 1 Mean (SE)	Trial 2 Mean (SE)	Trial 3 Mean (SE)	Trial 4 Mean (SE)	Trial 5 Mean (SE)	Trial 6 Mean (SE)	Mean difference over the six measurement trials (*p*)
Velocity (cm/s)	160 .06 (2.43)	156 .47 (2.43)	156 .24 (2.43)	156 .82 (2.43)	162 .29 (2.43)	158 .35 (2.43)	0.06
Cadence (steps/min)	117 .59 (1.47)	117 .93 (1.47)	117 .49 (1.47)	117 .72 (1.47)	117 .21 (1.47)	118 .53 (1.47)	0.03*
Double support left (%GC)	16 .41 (0.71)	17 .22 (0.71)	16 .86 (0.71)	16 .86 (0.71)	17 .14 (0.71)	17 .65 (0.71)	0.21
Double support right (%GC)	16 .41 (0.71)	17 .22 (0.71)	16 .86 (0.71)	16 .86 (0.71)	17 .14 (0.71)	17 .65 (0.71)	0.21
Swing time left (%GC)	41 .88 (0.37)	41 .19 (0.37)	41 .53 (0.37)	41 .53 (0.37)	41 .21 (0.37)	41 .08 (0.37)	0.03*
Swing time right (%GC)	41 .69 (0.44)	41 .50 (0.44)	41 .42 (0.44)	41 .59 (0.44)	41 .65 (0.44)	41 .82 (0.44)	0.96
Stance left (%GC)	58 .13 (0.92)	58 .47 (0.92)	58 .35 (0.92)	58 .28 (0.92)	58 .75 (0.92)	58 .58 (0.92)	0.36
Stance right (%GC)	58 .45 (0.40)	58 .37 (0.40)	58 .45 (0.40)	58 .40 (0.40)	58 .38 (0.40)	58 .59 (0.40)	0.98

*$p < 0.05$.

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The results indicated systematic differences between the spatiotemporal gait parameters measurements made by two measurement systems. The RehaWatch® system overestimated velocity (+ 2.7%) and swing time of left (+ 2.9%) and right side (+ 3.2%) and underestimated double support time of left (−17.3%) and right side (−16.8 %) and stance time of left (−2.3%) and right side (−2.1%). No systematic difference was found for cadence.

Although there were significant differences in most of the spatiotemporal gait parameters between the two measurement systems, these differences were clinically small. These systematic differences could be caused by the different measurement algorithms or differences in methodology used in the systems examined. RehaWatch® measures the acceleration and angular velocity while Gaitrite® measures pressure distribution under the foot. Based on these different quantities and the timing differences of the sensors between the systems, the calculation of the gait events is supposed to occur differently. In the RehaWatch® system the measuring sensors are attached to the lateral ankle on the shoe a few centimetres (3–4 cm) higher than the pressure mat of GAITRite®. This may cause the sensors of the RehaWatch® system to recognize the heel contact earlier and the toe lift-off later in the gait cycle than the pressure sensors of the GAITRite® mat. In addition, the calculation of the stride length with GAITRite® is different from RehaWatch®. GAITRite® calculates the stride length as the distance between two initial heel pressure points of the same foots.

In this study, we wanted to assess the repeatability of several different consecutive measurement trials during the same session because of missing knowledge concerning this primary issue. The repeatability of the spatiotemporal gait parameters of RehaWatch® seemed to be good despite of the fact that the gait distance was relatively short. In the previous studies the body-worn sensor technology has been reported to be valid and reliable for gait that is performed over walking distances even exceeding 20 m (Levangie & Norkin; Schwesig et al., 2010). The repeatability of RehaWatch® between three different days has also been reported to be high (Schwesig et al., 2010). Some reasons for our good repeatability results could be the carefully practiced and performed measurements by the same well-trained examiner and the well-standardized measurement sessions. Moreover, the normal preferred walking rhythm of each subject was carefully determined and settled to the metronome in order to standardize the individual walking pace. However, statistically significant difference between the six measured trials was found in terms of cadence (p = 0.03) and swing time of the left side (p = 0.03). It may be natural that there is some minor individual variation in cadence despite of beforehand set preferred walking rhythm that was instructed to be followed carefully. We cannot accurately explain the difference between the trials of swing time of the left side. The changes in those values could be related with the technical problems or steadiness of the measurement device with sensors in the level of the ankle. However, these variations of recorded values of cadence (117.21–118.53 steps/min) and swing time of the left side (41.08–41.88%) are so minor that they may have no clinical meaning.

In the study the test–retest repeatability of gait parameters measured using RehaWatch® was analyzed with a hierarchical linear mixed model. With this model it is possible to study whether there is a mean swift over the six trials and if the swift is different between the trials. It is a powerful tool where correlation between the trials is also modelled. Also, the model allows to analyze the data if there are some random missing data for example due to technical problems. From this model also the intra-class correlation coefficients (ICC) can be derived.

The greatest benefits of RehaWatch® over the laboratory-based gait analysis are that it can be used to collect and analyze steps in natural free-living environments. RehaWatch® provides a possibility to simulate natural continuous walking with a large number of steps which has been reported to make the gait reliable and less variable (Galna et al., 2013). In addition, the RehaWatch® system has the benefit of being quick and simple to use, and it is inexpensive, being attractive and user-friendly to clinicians. The RehaWatch® system seems to be quite a

useful gait measurement device in healthy subjects. The spatiotemporal gait information obtained with this measurement system might also be used for clinical assessments and treatment or physical therapy planning and evaluation of different patient groups.

However, we cannot make a statement regarding the validity and reliability of RehaWatch® in other populations, such as people with different diseases, pathologies or difficult gait disorders. When measuring gait parameters with RehaWatch®, the gait characteristics of subjects should be considered. It may be difficult to use RehaWatch® for subjects who walk with very short steps or the step length is shorter than the foot's length. There may also be difficulties with the measurement of RehaWatch® if the subjects drag the foot or feet or use different assistive walking devices. In addition, the RehaWatch® system recognizes the heel-strike as the primary gait event (gait events are calculated in relation to heel-strike) and it may be difficult to sense and recognize the heel-strike as the first contact to the ground in patients with difficult gait disorders, such as in difficult neurological child patients.

More research and evidence are strongly needed on the psychometric and feasibility properties in subjects with different diseases, pathologies and different kind of gait disorders.

Conclusion

This study showed that the RehaWatch® system seems to be a valid and mostly repeatable method for the assessment of spatiotemporal gait parameters of healthy young adults. However, the measurement results of the RehaWatch® system are not entirely comparable with the results of Gaitrite® system and the RehaWatch® system is recommended to be used consistently and carefully for clinical and research purposes.

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Competing Interest
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