Evaluation of Gait Parameters Determined by InvestiGAIT against a Reference System

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Abstract: The purpose is to investigate the validity of an inertial-sensor based gait analysis system (InvestiGAIT) consisting of off-the-shelf sensors and an in-house capturing and analyzing software. The gait of five persons with transfermoral limb loss were captured with the inertial system (Shimmer sensors) and the motion capture system (Vicon) integrating two force plates chosen as reference system in this study. Eleven gait parameters are determined from the data of the captured gait sequences. These gait parameters were compared descriptively and statistically using boxplots, Bland-Altman-plots, including the mean of difference (MOD) and the limits of agreement (LoA), the standard error of the mean (SEM), the Wilcoxon test and the Pearson's correlation coefficient. A complete validity of the gait parameters was not assumed due to the different measurement methods and the impact of the IMU sensor attachment (on the lower shank above the ankle). For the sound and the amputated leg four gait parameters show no significant difference (stride duration, cadence, velocity, stride length). All the other parameters have a p-value smaller than 0.05. Most of the gait parameters have a small MOD, SEM and LoA. These values show a very small absolute difference between the gait parameters of both systems. Based on the results the InvestiGAIT system can be assumed as valid and suitable for follow-up investigations of human gait in research projects or the clinical environment. Nevertheless, further investigations with healthy subjects and a sensor attachment on the subjects' shoe are planned.

1 INTRODUCTION

The instrumental gait analysis is a well-known examination method. The gold standard of the instrumental gait analysis are motion capture systems, such as Vicon, combined with force plates (Richards, 1999; Azad, 2009). Due to the costs and time which are related to an examination, that established method is only available for university hospitals and research centers. Smaller institutions or physiotherapeutical units do not have either the time during the therapeutic process nor the money to purchase such a system (Cloete and Scheffer, 2008). In the daily routine the gait analysis is done visually or with the assistance of simple video recording. The latter is useful to show the patient's existing deviations from the normal gait. This is a supporting tool used to be sensible for gait anomalies. For that purpose the visual recording is very useful, but it cannot be used for quantifying these anomalies. Inertial measurement units (IMU) could be helpful for that application area and necessary for follow-up examinations. (Cuesta-Vargas et al., 2010)

Due to the technical development IMUs are nowadays small in size, cost-efficient and permit a fast and easy analysis of the human gait. Our system called InvestiGAIT consists of two to four IMU (Shimmer) and the in-house capturing and analyzing software are used in different projects in teaching and research. Before such an inertial-sensor based gait analysis system can be used in the clinical environment the reliability, validity and objectivity of the system has to be checked (Atkinson and Nevill, 1998). The reliability was already investigated and results are prepared for publication.

Schwameder et al. (Schwameder et al., 2015) examined the validity of the GaitUp system (Physiolog4, GaitUp System, Lausanne, Switzerland, 200 Hz) under normal and limping gait conditions. The sensors are attached directly to the shoes of the subjects. Aspects of validity are given for five gait parameters as absolute differences between the both system, as correlation coefficient and Bland-Altman plots.

The aim of that paper is to present the results of the validity examination. The gait parameters determined

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by InvestiGAIT are compared to those parameters determined by the reference system, the motion capture system Vicon. Due to the fact that the gait parameter stride length can be calculated in different ways, three methods are presented. The results are compared to the stride length determined by the Vicon system. The most valid calculation method should be specified and used in further investigations.

2 METHODS AND MATERIALS

The gait of five persons with transfemoral limb loss was captured with Shimmer sensors (9-DoF-Sensors, Shimmer, Dublin, Ireland) and the motion capturing system Vicon (Vicon Motion Systems Ltd. UK). In parallel the gait sequences were recorded with a digital camera. The Shimmer sensors were attached laterally to the lower shank above the ankle. The Vicon system consisted of 12 infrared cameras and was synchronized with two force plates (AMTI, AMTI Force and Motion, Watertown, USA). 36 passive markers were attached to the body of the subject to capture the motion of the body during the gait sequences. The full-body markerset Plug-In-Gait was used to detect the gait events and calculate the gait parameters. The measured motion signals (acceleration and angular velocity) were analyzed with an in-house software (InvestiGAIT) implemented in MATLAB (TheMathworks Inc., Natick, MA, USA).

Figure 1: Marker and sensor placement on the amputated leg.

The gait events (initial and terminal contact, IC and TC) were detected from the angular velocity signal of the z axis representing the rotation in the sagittal plane. The gait events are defined as the local minima (IC and TC) and maxima (midswing) of the gyroscope signal described in (Orlowski and Loose, 2013) similar to (Greene et al., 2010; Mannini and Sabatini, 2012; Hundza et al., 2014). The heel contact (IC) is detected using a threshold of 20 N based on the force plates. Without the force plates the height of the heel marker is used to detect the heel contact. In case of the inertial sensors the motion of the lower shank is tracked during the gait. It is known that the detected IC and TC events correspond to the events detected by the reference system, but are not identical.

2.1 Setting

The group of subjects consisted of four men and one woman. The age was 47.7 ± 10.3 years, the duration of wearing the prosthesis was 23.2 ± 21.8 years, the height of the subjects was 176.8 ± 6.3 cm with body weight of $89,6 \pm 17.6$ kg. Two subjects have the prosthesis on the right and three on the left side.
Each subject walked a 12 m line straight forward with his/her normal self-selected speed. The gait sequence was repeated at least 12 times.
Vicon measurements were classified as valid when only one single foot contact was registered for each force plate. Some inertial measurements had to be rejected due to storage errors. Consequently, only nine to ten gait sequences per subject were analyzed. From the whole gait sequence only the gait cycle, which was done on the force plate, was investigated by both systems.
For both systems the gait cycles made on the force plates was investigated. In case of the IMU analysis, the additional video recording was used to find out which gait cycles were done on the force plates. A visual inspection of the video recording has to be conducted.

2.2 Gait Parameters

The gait parameters are calculated by stride-by-stride based algorithm after detecting the gait events TC, midswing, and IC of each leg from the angular velocity signal in the sagittal plane (see figure 2). The validity of the following gait parameters listed and described below were investigated:

- **Stride Duration [s]:** duration from one IC to the next IC
  $stride_i = IC_{i+1} - IC_i$
- **Swing Duration [s]:** duration from TC to IC
  $swing_i = IC_i - TC_i$
- **Single Leg Support [s]:** duration of the stance phase while the contralateral leg has no contact to the ground, corresponds to the swing phase of the contralateral leg given as example for the right leg
  $SLS_{R_i} = swing_i^L$

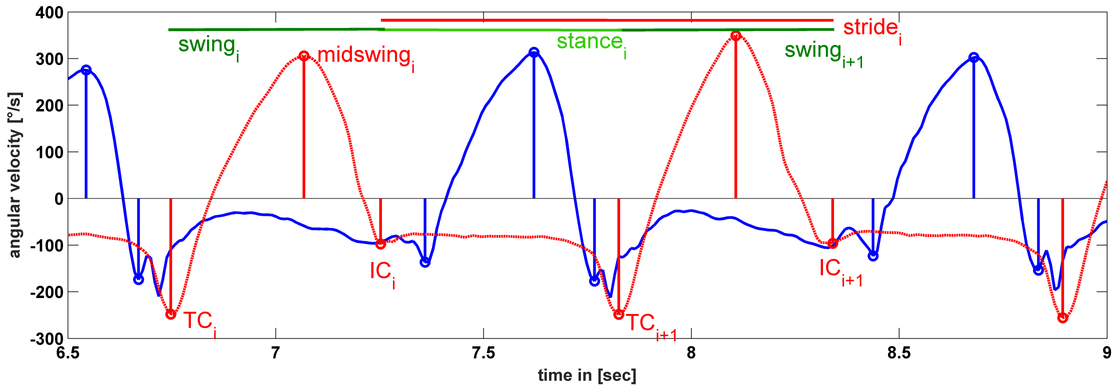

Figure 2: Angular velocity of the sound (blue solid) and amputated leg (red dotted) with marked gait events and gait parameters - stride, stance and swing (step).

- **Double Leg Support [s]:** duration of the contact of both legs to the ground, comprise of initial and terminal double leg support given as example for the right leg
  $DLS^R_{initial_i} = TC_R - IC_L$,
  $DLS^R_{terminal_i} = TC_L - IC_R$,
  $DLS^R_i = DLS^R_{initial_i} + DLS^R_{terminal_i}$
- **Cadence [Steps/min]:** step frequency; number of steps ($stepsL$, $stepsR$) during the gait sequence ($duration$) related to a one minute walk
  $cadence = 60 * ((stepsL + stepsR)/duration)$
- **Velocity [m/s]:** the average velocity calculated by the known distance (l) divided by the duration of the gait sequence ($velocity = l/duration$)
- **Stride Length (Acc) [m]:** stride length calculated by the integration of the acceleration of the horizontal sensor axis (x-axis)
  $strideLengthAcc = \iint a_x \, dt^2$
- **Stride Length (Dist) [m]:** known distance (l) divided by the number of steps of the considered leg
  $strideLengthDist = l/steps$
- **Stride Length (Vel) [m]:** stride duration multiplied by determined velocity
  $strideLengthVel = stride * velocity$

As the list above shows the stride length is determined in different ways. The first calculation method is based on the double integration of the acceleration in the horizontal direction (strideLengthAcc). As known from other investigation (Orlowski and Loose, 2014) or from the literature (Thong et al., 2002) that inertial sensors (in particular accelerometer) suffer from noise and drifts which are accumulated with time during the integration process. A priori knowledge or additional sensors are necessary to avoid errors in the distance estimation (Latt et al., 2011). Due to the fact that the sensor's coordinate system rotates during the swing phase of the leg, a projection would be necessary to get the real acceleration in the horizontal axis. Without this projection an overestimating of stride length is assumed. Alternatively, the stride length (strideLengthDist) can be calculated if the walked distance and the number of steps during the walking sequence are known or automatically determined. The stride length is the ratio of the entire distance and the number of steps. The third calculation method (strideLengthVel) is the product of the stride duration (in seconds) and the average velocity (meter per seconds).

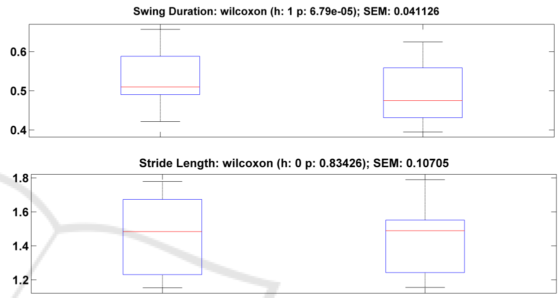

Figure 3: Boxplots of the gait parameters swing duration and stride length (Vel). Left the distribution of the parameter determined by InvestiGAIT and right of the Vicon system.

The gait parameters were determined for both legs: the amputated and the sound leg. Due to the fact that some of the subjects had the prosthesis on the left and others on the right side, the investigations referred to the amputated and sound side.

2.3 Statistics

To investigate the validity of the inertial-sensor based gait analysis system the values of the gait parameters were compared with those of the Vicon system. Therefore, boxplots of each parameter were prepared. Furthermore, Bland-Altman-Plots were

created to find the mean of differences (MOD), its standard deviation as well as the limits of agreement (LoA) between the values of both systems (Atkinson and Nevill, 1998; Bland, 1986). Based on the Kolmogorov-Smirnov-test the existing datasets were inspected regarding normal distribution. In presence of normal distribution the Students T-test and Pearson's correlation coefficient was conducted. Otherwise, in case of not normal distributed data, the Wilcoxon rank sum test and the Spearmans Rho was used. The level of significance was set to $= 0.05$. The strength of the correlation coefficient is based on the assessment scheme of Pavetic: weak ($r < 0.2$), low ($r > 0.2$ & $r < 0.4$), moderate ($r > 0.4$ & $r < 0.7$), strong ($r > 0.7$ & $r < 0.9$) and very strong $r(> 0.9)$ (Pavetic, 2015). Additionally, the standard error of the mean (SEM) was calculated.
All the calculations and statistical analyses were done in the MATLAB programming environment.

3 RESULTS

Figure 3 shows the boxplots for the swing duration and the strideLengthVel of the amputated leg. In both cases the distribution of the values of both systems (Inertial and Vicon) seems to be similar. Nevertheless, as the further investigation will be shown the difference of the gait parameter swing duration is more pronounced than that of the StrideLengthVel.
Tables 1 and 2 present the results of the absolute validity test in terms of the MOD, its standard deviation, the SEM, the LoA, the p-value of the Wilcoxon test and the correlation coefficient (Spearmans Rho). The gait parameters stride duration, cadence, velocity and strideLengthVel have p-values larger than 0.05 for both sides (sound and amputated) which means that these parameters have no significant difference and show a good agreement with the reference system.
Figure 4 shows the Bland-Altman plots of the gait parameters: stride duration and stride length (strideLengthVel) of the amputated leg. The MOD, its standard deviation and the LoA is given for each parameter. The MOD and its standard are for both parameters very small showing a good agreement of both systems. These parameters are those that show no significant difference between both systems (see tables 1 and 2).
For the most gait parameters of both legs the MOD, its SD and the LoA are similar. As the summarized values in the tables 1 and 2 demonstrate, there are only small differences between the gait parameters of the amputated and sound leg determined by the systems. Considering the SEM of the gait parameters it is a bit

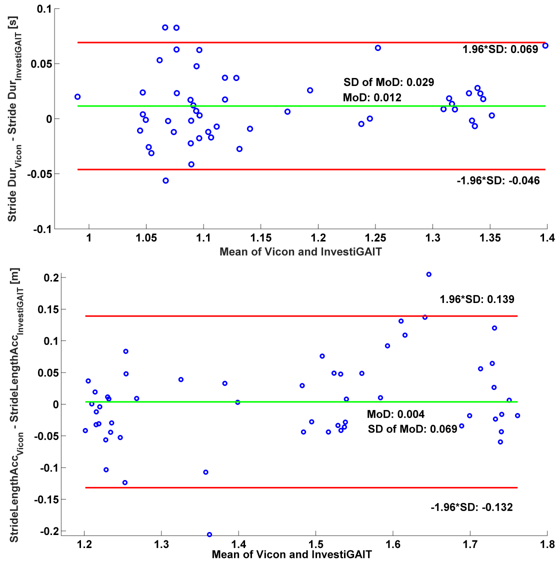

Figure 4: Bland-Altman Plots of the gait parameters stride duration and stride length (Vel) of the amputated leg. The MOD, its standard deviation and the limits of agreement are presented.

higher for the amputated leg regarding the parameters stride duration, cadence, velocity, and single support. The values of the gait parameters of the sound leg determined by InvestiGAIT correlate a bit better with those values of the chosen reference system Vicon than the parameters of the amputated leg. Six parameters have a large correlation coefficient greater than 0.7. According to Cohen (Cohen, 1988), these correlations can be seen as strong.

Tables 1 and 2 depict that the parameter strideLengthVel has a good agreement to the stride length which is determined by the Vicon system. The p-values larger than 0.05 ($p_{amputated} = 0.88$ and $p_{sound} = 0.83$) establish that there is no significant difference between the parameters. In contrast, the other parameters (strideLengthAcc and strideLengthDist) show a significant difference. Furthermore, the MOD is larger than that of the parameter strideLengthVel. The same applies to the SEM which is larger. It has to be noted that the parameter strideLengthAcc perform worst of the three alternatives.

4 DISCUSSION

A complete validity of the gait parameters of the inertial-sensor based gait analysis system (InvestiGAIT) with gait parameters of the reference system was not expected because of the different measurement principals. The gait events, initial and terminal contact, are determined in different ways

Table 1: Sound leg: Statistical values (Mean of the Difference (MOD), SD of MOD, standard error of the mean (SEM), limits of agreement (LoA), p-value of the Wilcoxon test, correlation coefficient) for all gait parameters as the difference of both systems. The asterisk characterizes the values showing no significant difference between the measurements of the two systems.

param	MOD	SD (MOD)	SEM (95 %)	LoA	p-value	correlation
stride [s]	-0.003	0.027	0.037	-0.06 to 0.05	0.779*	0.887
swing [s]	-0.137	0.068	0.094	-0.27 to -0.00	0.000	-0.454
single support [s]	0.043	0.026	0.036	-0.01 to 0.09	0.000	0.872
double support [s]	-0.161	0.073	0.101	-0.30 to -0.02	0.000	0.565
cadence [steps/min]	0.409	2.664	3.693	-4.81 to 5.63	0.779*	0.887
velocity [m/s]	-0.013	0.059	0.081	-0.13 to 0.10	0.839*	0.953
strideLengthAcc [m]	0.496	0.470	0.652	-0.43 to 1.42	0.000	-0.482
strideLengthDist [m]	-0.178	0.116	0.160	-0.40 to 0.05	0.000	0.830
strideLengthVel [m]	-0.006	0.077	0.107	-0.16 to 0.15	0.834*	0.889

Table 2: Amputated leg: Statistical values based on the difference of both considered systems (mean of differences (MOD), SD of MOD, standard error of the mean (SEM), limits of agreement (LoA), p-value of the Wilcoxon test, correlation coefficient) for all gait parameters. The asterisk characterizes the values showing no significant difference between the measurements of the two systems.

param	MOD	SD (MOD)	SEM (95 %)	LoA	p-value	correlation
stride [s]	0.012	0.029	0.041	-0.05 to 0.07	0.448*	0.841
swing [s]	-0.084	0.041	0.057	-0.16 to -0.00	0.000	0.835
single support [s]	0.034	0.044	0.061	-0.05 to 0.12	0.000	0.335
double support [s]	-0.218	0.073	0.101	-0.36 to -0.07	0.000	0.358
cadence [steps/min]	-0.997	2.882	3.994	-6.65 to 4.65	0.448*	0.841
velocity [m/s]	-0.018	0.062	0.085	-0.14 to 0.10	0.811*	0.968
StrideLengthAcc [m]	0.123	0.395	0.548	-0.65 to 0.90	0.001	-0.166
StrideLengthDist [m]	-0.114	0.082	0.113	-0.27 to 0.05	0.001	0.882
StrideLengthVel [m]	0.004	0.069	0.096	-0.13 to 0.14	0.881*	0.890

and it is known that IC and TC of both systems are corresponding but not identical. Consequently, the derived gait parameters are similar. For the most of the parameters a small deviation was expected. Similar results were published by (Böhme, 2012; Derlien et al., 2010)

This expectation was confirmed by the results of the Wilcoxon test whose p-values show a significant difference between both systems for the most gait parameters. Although, the other results in terms of the MOD, SEM and LoA prove the similarity of the gait parameters determined by the different systems.

The results of the validity examination of Schwameder et al. (Schwameder et al., 2015) are similar to our results. The authors present correlation coefficients and LoA. The correlation coefficients are comparable and in three cases smaller (stride duration 0.887 vs 0.986, stride length 0.889 vs 0.951, cadence 0.887 vs 0.981) in one case a bit smaller (velocity 0.953 vs 0.967) in our system. Schwameder et al. presented the limits of agreement for one gait parameter (velocity) in visual way (Bland-Altman plots) without given the concrete value. That is why the LoA are hardly comparable to those achieved in our examination due to the fact that different speeds of limping walking are integrated in the analysis. The LoA are slightly narrower (-0.13 to 0.10 vs -0.6 to 0.9) in comparison to our system.

The investigation of the different calculation method for determining the gait parameter stride length show remarkable differences between the three methods. The best agreement with the reference system was achieved by the parameter strideLengthVel which involves the stride duration and the average velocity. The parameter strideLengthAcc which based on the integration of the horizontal acceleration demonstrates the worst agreement with the Vicon measurements. The reasons are that no a priori knowledge is used in the proposed stride-by-stride algorithm, no additional sensors, such as magnetometers, are used to reliably estimate the position of the sensor during walking, and a projection of the acceleration to the horizontal axis was not conducted. An impact on the missing validity of that parameter is the chosen position of the sensor on the lower shank. Other investigations have shown that the double integration based on shoe-mounted sensors achieved excellent results in distance estimation (Loose and Orlowski, 2015b; Loose and Orlowski, 2015a). Singleton et al. (Singleton et al., 1992) published a study where they have shown that the prediction of step time from step length and average velocity is not a good choice for asymmetric gait patterns. In contrast to the step length / duration, the stride length and stride duration used in our algorithm are largely the same for both legs. Following the effect described by Singleton has no impact on our algorithm. Based on the achieved results in the present validity study using the average velocity and the stride duration for the determination of stride length, a valid method is found. Furthermore, the use of average velocity could affect negatively if the walking velocity is not constant during the walking sequence. Regarding further investigations in the clinical environment with patients having different asymmetries, the problem depicted by Singleton et al. (Singleton et al., 1992) should be kept in mind and a valid step length algorithm should be used in order to examine the asymmetric gait pattern of the patients.

5 CONCLUSION

At the end of these investigations we can conclude that the gait parameters determined by the inertial-sensor based gait analysis system InvestiGAIT show partly excellent agreement with those parameters determined by the reference system. Based on the results of the Wilcoxon test the agreement of four parameters have be presented. Furthermore, other parameters show a good agreement between the systems in terms of a strong correlation. Small MOD, SEM and LoA show similar effects. Consequently, the gait parameter determined by InvestiGAIT are assumed as valid and the system can be used in follow-up examinations.

Nevertheless, further investigation are planned with an adapted attachment of sensors on the subjects' shoe in order to get a higher conformity of the gait parameters. Furthermore, these measurements should be conducted with a group of subjects without any gait limitations in order to exclude the impact of the disease. In this connection another method for calculating stride length proposed by (Mercer and Chona, 2015) should be investigated regarding validity in relation to the reference system. They use the stride length as the ratio of velocity and stride frequency which is the number of foot contacts per second measured in Hertz (Magness, 2010).

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