Analyzing the Transfemoral Amputee Gait using Inertial Sensors
Identifying Gait Parameters for Investigating the Symmetry of Gait - A Pilot Study

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Abstract: The amputation of a lower limb is a drastic event and it completely changes the life of the person. Current development of prosthesis is already advanced, but most of the affected persons suffer from changes in the gait which are visible to the general public. The gait of transfemoral amputees was investigated in the laboratory environment and is called asymmetric due to different facts: shorter step length, smaller velocity and smaller cadence. The use of mobile inertial sensors can be supportive in the rehabilitation process of these patients. That is why a pilot study is conducted to evaluate the gait of transfemoral amputees and compare their gait parameters with those of the healthy subjects. The purpose of the investigation is to identify gait parameters showing the asymmetric properties of the amputees gait. Eight parameters seem to be distinctive and descriptive.

1 INTRODUCTION

The gait is an essential movement for getting from one place to another and therefore influencing the daily life of people. Consequently, human gait disorders, such as lower limb amputations, affect the quality of life. The familiarization with the prosthesis may take years and strongly depends on the adaptation to the prosthesis socket. Due to the fact that the human gait is a complex motion involving a lot of muscles, it is very important for amputee gait to improve the interaction of the remaining muscles. As known from the literature the transfemoral (TF) and -tibial (TB) amputee gait is asymmetric and gait parameters deviate from the normal gait (Murray, 1980; Goujou-Pillet et al., 2008). The relation between swing and stance phase differs significantly from the well-known 40-60-ratio (Perry, 2010); the cadence is much smaller ($p < .001$), the stride length much shorter ($p < .01$) and the walking speed much slower ($p < .001$) in amputees' gait (Murray, 1980). Goujou-Pillet et al. (Goujou-Pillet et al., 2008) show that (1) amputees have larger range of motion (ROM) in the upper body the slower they walk, (2) the pelvic rotation is specific and (3) the existing counter-rotation of the pelvic and the shoulder girdles is less present than in normal gait. The gait parameters in amputees gait are much more variable than in normal gait. In the literature there are various methods named for the assessment of the gait symmetry. Tura et al. (Tura et al., 2010) investigated the step and stride regularity using the unbiased autocorrelation coefficient and compares the results of those coefficients with defined symmetry index (SI). Petersen et al. (Petersen et al., 2010) use the absolute symmetry index (ASI) and the butterfly symmetry ratio (BSR) to decide whether the gait symmetry is significantly improved wearing different technologies of prosthesis. Ambrosini et al. (Ambrosini et al., 2011) considered the swing and stance ratio in percentage of stride of both legs to assess the impact of the 2-week training. The named parameters are calculated from autocorrelation function of the acceleration or angular velocity measured by inertial sensors. Furthermore, the authors reconstructed the kinematic signals of the opposite body side by employing the Principal Component Analysis (PCA) and achieve good results. Gouwanda (Gouwanda, 2012) compares the normalized SI and the normalized cross-correlation and can show that the gait of participants wearing a knee or ankle brace is significant asymmetric. Wang and Low (Wang and Low, 2009) used the autocorrelation to decide whether the gait is symmetric or not based on the muscle activity measured during the gait sequence. Other methods for investigating the gait symmetry are the clustering (Jiang et al., 2010), symbolization (Sant'Anna and Wickström, 2010) or

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classification by neural networks (Wafai et al., 2013; Wafai et al., 2014). The SI proposed by Robinson et al. (Robinson et al., 1987) is most often mentioned in the literature.

To evaluate the gait of a person different methods are conceivable and generally accepted in the medical environment. Muro-de-la-Herran et al. (Muro-de-la-Herran et al., 2014) gave an overview of various methods. They differentiated between non-wearable and wearable systems used in the clinical field. They emphasized the advantages of the mobile systems, but also referred to possible drawbacks of sensor accuracy. Motion capture systems, such as Vicon, were regarded as gold standard. They mentioned inertial measurement units (IMU) as sensor types which are the most popular in the wearable gait analysis (with almost two-thirds of the total number of wearable systems). On this account and due to the simplicity of the usage of IMUs in the motion analysis, our focus is on the development of automatic methods for the analysis and evaluation of human gait based on IMU using those distributed by Shimmer Research / Shimmer Sensing[1].
This paper presents common gait parameters determined by using two inertial sensors. The identification of characteristic features of the amputee gait is based on the comparison of the gait parameters of TF amputees with those of the normal gait.

2 METHODS AND MATERIALS

In this section the determination of gait parameters based on the data measured using two inertial sensors (acceleration and angular velocity) is presented. Furthermore the conducted experiments are briefly explained. A short description of the used sensors is included in the subsection 2.2.

2.1 Gait Parameters

Using two inertial sensors attached to the lower shank above the ankle, 20 gait parameters (as mean and std) are automatically determined by various algorithms. Only two of the three axes of the acceleration (horizontal and vertical) and one of the three axes of the angular velocity are necessary for the calculation of the parameters. Most of them are based on the angular velocity about the sagittal plane ($angVel_z$) and the detection of the gait events - initial and terminal contact (IC and TC). The gait events are characterized by two local negative peaks within the signal of the angular velocity of the sagittal plane. Others are calculated by integrating the acceleration or angular velocity.

Further information about the used algorithms can be found in former publications (Orlowski and Loose, 2013; Orlowski and Loose, 2014).

Features describing the gait symmetry are the step length and the stance ratio (Götz-Neumann, 2011). The first feature is not considered in this investigation. The second gait symmetry feature is included and can be analyzed by considering the parameter *stance (St)* for both sides (left, right). For each of the determined parameters the symmetry index based on Robinson et al. (Robinson et al., 1987) is calculated using the following equation 1:

$$SI[\%] = \frac{x_{right} - x_{left}}{\frac{1}{2} * (x_{right} + x_{left})} * 100 \qquad (1)$$

with x_{right} and x_{left} representing a gait parameter measured for the left and right side.

The gait is assumed symmetric if SI of one or more parameters are close to zero. Consequently, the greater the value deviates from zero in both directions (positive and negative), the more asymmetric is the gait. Due to the fact that the normal gait is not completely symmetric, it has to be defined which deviation is acceptable to call the gait as symmetric.
Based on the information given in the literature combined with the conducted evaluation of the gait parameters of all subjects (healthy and amputees) eight gait parameters are identified as distinctive and descriptive for the amputees gait:

- *midswing height (MH)*: mean of the amplitude during the midswing (see figure 1)
- *height difference between TC and IC (HD)*: mean difference of the amplitudes of the IC and TC (see figure 1)
- *swing (Sw)*: percentage of swing (TC-IC) at the gait cycle (IC-IC)
- *stance (St)*: percentage of stance (IC-TC) at the gait cycle (IC-IC)
- *single limb support (SLS)*: percentage of single limb support at the gait cycle (IC-IC)
- *put-on-angle (PA)*: maximum angle at the IC
- *cadence (C)*: steps per minute
- *velocity (V)*: distance per minute

2.2 Experiments

The gait of six healthy subjects (see table 1) and two patients (see table 2) was measured with two inertial

[1] www.shimmersensing.com

sensor capturing the acceleration and angular velocity. The sensors were each attached laterally on the lower shank above the ankle. The ”normal” gait of the subjects (healthy adults) and patients (TF amputees) were captured while walking (straight forward) between 10 and 20 meters at normal speed.

9-DoF sensors (Shimmer2r) were used, without registering the magnetometer, though it is not included in the experiments. The acceleration and angular velocity were measured with a frame rate of 102.4 Hz and a sensitivity of 6g for the accelerometer and 500 deg/s for the gyroscope.

The capturing was done using the software Multi-Shimmer-Sync provided by the manufacturer and an capturing software implemented in MATLAB® using the interface given by Shimmer Research. The analysis and evaluation was exclusively done in MATLAB®.

In the preliminary study two patients (TF amputees) participated in our experiments. As reference values the data (parameters and especially the SI) from healthy adults was used. As the table 1 show 385 gait cycles of 33 gait sequences were included to measure the reference values.

Table 1: Anthropometric data and information of the gait cycles (GC) of the six healthy subjects. For each subject four to seven gait sequences (GS) are registered.

Subject No.	**1**	**2**	**3**	**4**	**5**	**6**
age	29	37	42	32	25	25
BMI	27	25	23	22	21	21
sex	m	m	f	f	m	f
GS	4	5	6	7	5	6
GC	37	45	85	83	45	90

Table 2: Anthropometric data and information of the gait cycles of the two patients.

Patient No.	**1**	**2**
age	30	32
BMI	25	21
sex	m	m
GS	15	12
GC	93	72
prosthesis	left	right

3 RESULTS

After measuring the gait of the two patients, the stored data of the accelerometer and gyroscope was analyzed with the existing algorithms using the in-house development. The gait cycle of TF amputees gait have the characteristic events IC and TC. Therefore, the further analysis could be conducted without adjustment on the algorithms. The gait parameters were calculated for all datasets. Furthermore, all datasets of the healthy subjects were analyzed. Consequently, for each subject and each measurement a table including the parameters for the left and right leg was created. The symmetry was determined for each parameter using the SI value. Furthermore the mean values of the parameters (left and right side) and the SI values are calculated for all available gait sequences for each subject (two patients, six healthy) and for the group of healthy subjects and both amputees.

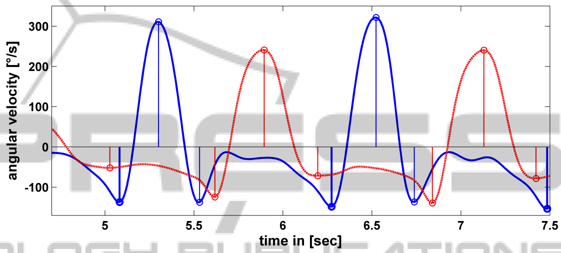

Figure 1: The angular velocity in the sagittal plane of the sound side (blue solid) and the amputated side (red dotted) with marked TCs (terminal contacts), midswings and ICs (initial contacts).

The tables 3, 4 and 5 show the parameters identified as descriptive and distinctive. Table 3 represents the gait parameters of a normal gait. The values in table 4 belong to a patient one with a TF prosthesis on the left side based on 15 gait sequences. The values in table 5 belong to a patient two with a TF prosthesis on the right side based on 12 gait sequences. The SIs in the tables represent the mean value of all gait sequences using the absolute value of each SI of the 33 gait sequences due to the fact that the measured subjects can have both a dominant right or left leg. The calculation of the mean based on the raw SI values (positives and negatives), would falsify the results because a positive value would compensate a negative one. In contrast to the SI which is unaffected by the dominance of one leg, this is not applied to the gait parameters presented in table 3. Consequently, the gait parameters of the healthy subjects can not be directly compared with those of the patients.

The main difference between the normal and amputees gait is the relation of swing and stance phase (*Sw* and *St*). The same applies to the ratio of single limb support and stride (*SLS*). These three parameters show a symmetric value for the normal gait (SI ranges from 2.16 to 3.66), while the amputees gait has larger deviations from zeros (SI ranges from 17.39 to 20.89 or 6.16 to 7.03). Furthermore the velocity and the cadence differs clearly. The figure 1 shows the angular velocity presenting the motion of the lower shank in the sagittal plane. The gait events midswing, IC and TC are marked for both sides (blue: sound and red: amputated). Clearly visible is the difference of the maximum amplitude during the swing phase of the amputated and sound side. Furthermore the TCs of the amputated side are much smaller than those of the sound side.

Table 3: Selected gait parameters of the normal gait given for the left and right side as well as the SI as mean values (standard deviation) of 33 gait sequences of the six healthy subjects. For calculating the mean SI of all healthy subjects the absolute value of each SI is used. (MH - midswing height, HD - height difference of TC and IC, Sw - swing, St - stance, SLS - single limb support, PA - put-on-angle, C - cadence, V - velocity).

Param	unit	left	right	SI [%]
MH	$^\circ/s$	305.47 (24.48)	317.79 (20.94)	9.77 (5.48)
HD	$^\circ/s$	21.24 (11.26)	16.11 (8.24)	57.23 (44.80)
Sw	%	47.4 (1.01)	48.3 (1.28)	2.33 (1.53)
St	%	52.6 (1.04)	51.7 (1.30)	2.16 (1.45)
SLS	%	48.5 (2.26)	48.0 (1.22)	3.33 (3.95)
PA	$^\circ$	12.03 (0.62)	12.88 (1.53)	11.10 (8.56)
C	$\frac{steps}{min}$	116.30 (3.23)	116.30 (3.23)	—
V	$\frac{m}{min}$	79.02 (5.56)	79.02 (5.56)	—

4 DISCUSSION

While the normal gait has a almost 50-50 ratio for both body sides in our setting, the amputees gait has this ratio on the affected side. The stance ratio on the unaffected side partly shows a distribution much closer to 40-60 %. In contrast to the common relation of swing and stance phase of 40-60 % (Perry, 2010), evaluating the gait of healthy subject we received almost a 50-50 % ratio. The determination of start and end point of the swing and stance phase are two reasons for that deviation. The investigation of the two patients show that TF amputees have a larger stance phase on the sound leg than on the amputated leg, as given in the literature (Murray, 1980).

As described by Götz-Neumann (Götz-Neumann, 2011) the mean stride length, consequently the *velocity* differs significantly between the two groups of subjects. The normal gait (normal speed) achieves a velocity of about $79m/min$, the amputees gait reaches a velocity of about $63m/min$. Due to the fact that the velocity is a parameter which is not calculated separately for each side, no symmetry value is derived.

The gait parameter *put-on-angle* is distinctive: in normal gait the angle is always larger then ten degrees

Table 4: Selected gait parameters of the amputees gait (patient one) given for the amputated and sound side as well as the SI as mean values (standard deviation) of 15 registered gait sequences.

Param	unit	amputated	sound	SI [%]
MH	$^\circ/s$	278.91 (3.50)	257.32 (4.56)	8.06 (1.51)
HD	$^\circ/s$	122.06 (4.19)	43.36 (6.96)	95.56 (13.06)
Sw	%	52.5 (1.33)	43.1 (0.67)	18.68 (3.39)
St	%	47.5 (1.07)	56.9 (0.72)	17.39 (2.69)
SLS	%	42.1 (0.75)	51.9 (1.18)	20.89 (3.21)
PA	$^\circ$	12.83 (0.31)	8.16 (0.28)	44.49 (3.21)
C	$\frac{steps}{min}$	104.02 (1.44)	104.02 (1.44)	—
V	$\frac{m}{min}$	62.75 (4.53)	62.75 (4.53)	—

Table 5: Selected gait parameters of the amputees gait (patient two) given for the amputated and sound side as well as the SI as mean values (standard deviation) of 12 registered gait sequences.

Param	unit	sound	amputated	SI [%]
MH	$^\circ/s$	333.18 (8.44)	283.21 (9.38)	16.23 (1.42)
HD	$^\circ/s$	110.54 (4.49)	61.22 (8.48)	58.01 (11.66)
Sw	%	45.5 (0.61)	48.4 (1.28)	6.16 (3.37)
St	%	54.5 (0.52)	51.6 (1.18)	7.03 (2.84)
SLS	%	48.5 (1.35)	45.5 (1.39)	6.93 (4.75)
PA	$^\circ$	13.23 (0.47)	14.46 (0.96)	10.05 (5.47)
C	$\frac{steps}{min}$	109.56 (3.23)	109.56 (3.23)	—
V	$\frac{m}{min}$	62.84 (3.03)	62.84 (3.03)	—

and depends on the walking velocity, within the amputees gait the angles never reaches ten degrees for sound side. The *put-on-angle* of this subject is seen as asymmetric due to its SI value of 44.49.

Further parameters which refer to an asymmetry in the amputees gait are *MH* and *HD*. Both are partly characteristic and can even be detected through visual inspection of the gyroscope data. Within the gait cycle of the normal gait the difference of the amplitudes at the events IC and TC are almost the same for both legs (*HD*). Considering the amputees gait there is an imbalance of that difference regarding the affected and the unaffected body side (see figure 1). This is reflected by the calculated SI value of patients one (normal 57.23 and amputee one 95.56 and two 58.01). Regarding the parameter *MH* the deviation is much smaller, but it is recognizable in the SI value for one of the patients (normal 11.10 and amputee one 44.49 and two 10.05). Considering the results of the experiments, there are three to five gait parameters for the motion of the foot (lower shank) which show a difference and therefore descriptive for the assessment of the symmetry. As the tables 4 and 5 show that the gait of amputees is not comparable due to different facts: duration of wearing prosthesis, length of the stump, type of the knee joint and others.

5 CONCLUSIONS AND OUTLOOK

The determination of the gait parameters based on the algorithms is equal for both, the normal and the amputees gait. The symmetry of the gait is calculated for each parameter using the symmetry index of Robinson et al. (Robinson et al., 1987). A group of eight is chosen from the 20 parameters. The parameters *HD*, *Sw*, and *St* (*SLS*) characterize the asymmetric gait of TF amputees in comparison to the normal bipedal gait. The gait parameters *MH*, *PA*, and *V* are useful for the identification of an amputees gait. These seem to be descriptive and distinctive in terms of characterizing the gait of healthy adults and those affected by amputation as well as showing the existence of symmetry. Whether these parameter are correct will be evaluated in the following study with TF amputees where the gait analysis based on inertial sensors is intended to use as pre- and posttest.

In addition to the changed swing-stance-relation an oscillating motion of the upper body is characteristic for the amputees in comparison to the normal gait (Goujou-Pillet et al., 2008). These motion can not be registered with two sensors attached to the lower shank, though. Consequently, our gait analysis has to be expanded to the upper body by using additional sensors. Furthermore it is necessary for the evaluation in the pre- and posttest of the following study with TF amputees to have more measurements of normal gait.

REFERENCES

Ambrosini, E., Ferrante, S., Pedrocchi, A., Ferrigno, G., Guanziroli, E., and Molteni, F. (2011). A novel biofeedback cycling training to improve gait symmetry in stroke patients: A case series study. *IEEE International Conference on Rehabilitation Robotics (ICORR)*, pages 1–6.

Götz-Neumann, K. (3. Auflage, 2011). *Gehen verstehen - Ganganalyse in der Physiotherapie*. Georg Thiem Verlag KG.

Goujou-Pillet, H., Sapin, E., Fod, P., and Lavaste, F. (2008). Three-dimensional motion of trunk and pelvis during transfemoral amputee gait. *Arch Phys Med Rehabil*, 89:87–94.

Gouwanda, D. (17-19 December 2012). Further validation of normal symmetry index and normal cross-correlation in identifying gait asymmetry on restricted knee and ankle movement. *IEEE Conference on Biomedical Engineering and Sciences*, pages 423–427.

Jiang, S., Zhang, B., Xu, W., and Wei, D. (2010). Gait symmetry analysis based on affinity propagation clustering. *IEEE 10th International Conference on Computer and Information Technology (CIT)*, pages 1673–1678.

Muro-de-la-Herran, A., Garcia-Zapirain, B., and Mendez-Zorrilla, A. (2014). Gait analysis methods: An overview of wearable and non-wearable systems, highlighting clinical applications. *Sensors*, 14:3362–3394.

Murray, M. P. (1980). Gait patterns of above-knee amputees using constant -friction knee components. *Bulletin of Prothetics Reserach*, 17 (No. 2):35–45.

Orlowski, K. and Loose, H. (2013). Evaluation of kinect and shimmer sensors for detection of gait parameters. *Proceedings of BIOSIGNALS 2013, Int. Conference on Bio-Inspired Systems and Signal Processing, Barcelona, Spain, 11-14 Feb. 2013*, pages 157–162.

Orlowski, K. and Loose, H. (2014). Simple algorithms for the determination or the walking distance based on the acceleration sensor. *Proceedings of BIOSIGNALS 2014, Int. Conference on Bio-Inspired Systems and Signal Processing, Angers, France, 3-6 March 2014*, pages 264–269.

Perry, J. (2010). *Gait Analysis - Normal and Pathological Function*. Slack Inc.

Petersen, A. O., Comins, J., and Alkjr, T. (03/2010). Assessment of gait symmetry in transfemoral amputees using c-leg compared with 3r60 prosthetic knees. *JPO Journal of Prosthetics and Orthotics*, 22 (2):106–112.

Robinson, R., Herzog, W., and Nigg, B. (1987). Use of force platform variables to quantify the effects of chiropractic manipulation on gait symmetry. *Journal of Manipulative and Physiological Therapeutics*, 10 (4):172–176.

Sant'Anna, A. P. and Wickström, N. (2010). A symbol-based approach to gait analysis from acceleration signals: Identification and detection of gait events and a new measure of gait symmetry. *IEEE Transactions on Information Technology in Biomedicine*, 14 (No. 5):1180–1187.

Tura, A., Raggi, M., Rocchi, L., Cutti, A. G., and Chiari, L. (2010). Gait symmetry and regularity in transfemoral amputees assessed by trunk acceleration. *Journal of NeuroEngineering and Rehabilitation*, 7:4.

Wafai, L., Zayegh, A., Begg, R., and Woulfe, J. (2013). Asymmetry detection during pathological gait using a plantar pressure sensing system. *7th IEEE Conference and Exhibition (GCC)*, pages 182–187.

Wafai, L., Zayegh, A., Woulfe, J., and Begg, R. (2014). Automated classification of plantar pressure asymmetry during pathological gait using artificial neural network. *Middle East Conference on Biomedical Engineering (MECBME)*, pages 220–223.

Wang, P. and Low, K. (2009). Qualitative evaluations of gait rehabilitation via emg muscle activation pattern: Repetition, symmetry, and smoothness. *IEEE International Conference on Robotics and Biomimetics (ROBIO)*, pages 215–220.