This is a preprint of a paper that appeared in the Proceedings of the International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC), 2015, Milan

Measurement of Biomechanical Interactions at the Stump-Socket Interface in Lower Limb Prostheses

V. Noll[1], J. Wojtusch[2], J. Schuy[1], M. Grimmer[3], P. Beckerle[1], and S. Rinderknecht[1]

Abstract— **This paper introduces a novel measuring approach for detecting relative movement between stump and socket in lower limb prostheses. The application of the motion capturing based measuring approach is shown at a single male trans-tibial amputee using a Patella Tendon Bearing (PTB) socket. It further investigates and assesses the feasibility of measuring the relative movement between stump and socket during level walking at different velocities and allocating it to the coinciding loads. Representative results for the two translational degrees of freedom in the sagittal plane are presented and discussed. For the proximodistal (pd) direction, a linear correlation between applied load and relative movement is found, while for the anteroposterior (ap) direction the stump movement is largely influenced by the motion sequence during the respective gait event. Additionally, the effect of walking speed is discussed.**

I. INTRODUCTION

In the last decade there has been a vast development in lower limb prostheses. Mechatronic systems have enlarged their functionality and improved the quality of life for amputees [1], [2]. Nevertheless, the amputee's well-being and mobility are largely determined by socket fit and subsequent stump-socket interaction [3]. Today, the rectification process is mainly based on examining the stump in a seated position; the successful fitting depends primarily on the ability and experience of the prosthetist [4]. Quantitative knowledge about biomechanical interactions at the interface, particularly during gait, is rare. A possibility for gaining a better understanding of the interface is through analysis of interaction factors of well-fitted sockets. State-of-the-art research of the socket interface in lower-limb prostheses comprises socket pressure measurements, computational modeling and friction-related phenomena (including relative movement) [3].

Previous studies concerning relative movement between residual limb and prosthesis differ in the definitions of relative movement, used measurement system and examined loading condition. According to Klasson, the stiffness of the coupling between the skeleton and the socket is a significant factor in socket fit [5]. Several studies used radiography to analyze the residual tibial [6], [7], [8], [9] or femoral [10], [11] movement within the socket. Since the use of radiography is limited by the risk of ionizing radiation, these studies were restricted to static analysis. The applied loading conditions vary from static additional loads [9] to static reproduction of specific events of the gait cycle [8]. The use of ultrasound diagnostics permits the assessment of remnant bone movement during dynamic activities [12], [13]. Nevertheless, the discussed relative movement consists of movement of the remnant bone within the stump and of the stump itself in the socket, so that a differentiation between the two is useful. Commean et al. distinguish these two combining factors for a known static loading condition of a trans-tibial (TT) amputee [9]. Appoldt et al. investigated the relative movement between stump (skin) and socket of trans-femoral (TF) amputees using a custom-made slip gauge [14]. However, the measurement assembly prevents the allocation of the recorded relative movement to specific gait events.

The presented pilot study investigates and assesses the feasibility of recording the relative movement between stump and socket during straight level walking. The measuring approach used, which enables allocating the relative movement to specific gait events and applied load condition, is explained in Sec. II. The measurement approach gives insight into the biomechanic interaction at the interface by providing data of possible causes for the relative movement of the stump within the prosthetic socket. The results are presented and discussed in Sec. III. Finally, the paper is concluded and an outlook to future works is given in Sec. IV.

II. METHODOLOGY

Subsequently, the methodology of the data collection and evaluation is presented.

A. Measurement Concept

The factors considered for the biomechanical interaction at the stump-socket interface are the loads at the distal end of the socket as well as the relative movement between residual limb and socket. Three trials, which differ in walking speed, are recorded. Each trial consists of level walking on a treadmill at a constant walking speed. The speed levels are determined in pretests, which revealed the subject's favorite walking speed as 0.85 m/s. To vary the speed - a slower and faster walking speed are self-selected by the subject (0.65 and 1.05 m/s, respectively).

To measure the loads at the distal end of the socket, a custom-built measurement adapter [15] is used. This adapter is integrated into the prosthetic structure. Subject motions and relative movements at the stump-socket interface are recorded using motion capturing technique.

[1] Noll and colleagues are with the Institute for Mechatronic Systems in Mechanical Engineering, Department of Mechnical Engineering, TU Darmstadt, Germany

[2] Janis Wojtusch is with the Simulation, Systems Optimization and Robotics Group, Department of Computer Science, TU Darmstadt, Germany

[3] Martin Grimmer is with the Locomotion Laboratory, Institute of Sport Science, TU Darmstadt, Germany

978-1-4244-9270-1/15/$31.00 ©2015 EU

B. Measurement Arrangement

This pilot study is conducted with a single male participant. The subject is an active TT amputee (50 years, 95 kg, amputated for 25 years). The stump measures 14 cm in length. He has been using a PTB socket with a quick release adapter for the last three years and considers the socket to be a comfortable fit.

Using motion capturing technique to record the relative movement at the stump-socket interface requires a specific test socket in order to place markers directly on the stump. This socket was manufactured by a certified prosthetist using the existing plaster positive of the stump. The test socket features three cavities - one for positioning the knee marker and two for positioning markers to detect relative movement (cf. Fig. 1). The dimensions of the cavities on the socket pose a tradeoff between enabling relative movement notwithstanding the placement of markers, and ensuring the integrity of the socket and control of the prosthesis. Markers are attached to the outside surface of the residual limb liner and on the socket itself (cf. Fig. 1). With the placements used, relative movement in the sagittal- and frontal plane can be detected.

During gait, kinematics were recorded at 500 Hz using the motion analysis system QUALISYS OQUS300+ and QUALISYS OQUS310+. Kinetics were recorded at 1 kHz by the instrumented treadmill of type ADAL3D-WR and at 500 Hz by the custom-built measurement adapter. All systems were synchronized using a triggering signal (voltage change) from the treadmill system.

C. Analysis of Data

A sampling rate of 500 Hz is adapted for all measurement systems. Due to the magnitude of forces applied on the prosthesis, only stump-socket interaction during stance phase is considered. Heel-strike and toe-off are determined by the detected ground reaction forces (GRF). These two significant events of gait are used to identify the stance phase of each step.

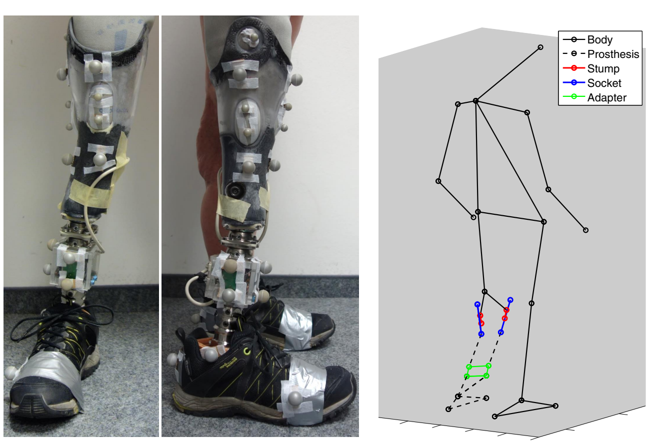

Fig. 1. Illustration of markers to track motions of the subject and relative movement between stump and socket: Positioning of markers (left) and consequent model of subject (right).

Kinematic and kinetic analysis of straight level walking has revealed little activity in the medio-lateral (ml) direction compared to the other directions [16]. Hence, only interaction in the sagittal plane is examined. The three-dimensional marker trajectories are projected into the sagittal plane for evaluation. This projection leads to a systematic error err_P. This error can be shown to be at an acceptable range for socket markers ($err_P \leq 2.5$ % cf. [18, Sec. 6.3.1]).

The relative movement is evaluated using the time-dependent positions of the socket axis defined by the two lateral socket markers and the lateral distal stump marker. The offset is compensated by using the measured loads of the adapter, defining the relative movement as zero for load-free conditions of the considered direction.

III. RESULTS AND DISCUSSION

Following, the results of the experimental trials are presented. Initially, the plausibility of the detected relative movement by the novel measurement approach is assessed through time series of gait data for the subject's favorite walking speed. Fig. 2 and 3 show the occurring load (top) and calculated relative movement (bottom) in the considered translational direction plotted over the stance phase. Displayed are mean and standard deviation of 59 consecutive steps. Subsequently, the influence of walking speed on the biomechanic interaction at the interface is investigated.

A. Proximodistal Direction

Fig. 2 indicates a close connection between occurring load and relative movement for the pd-direction: With increasing load the stump sinks deeper into the socket. This impression is supported by the cross correlation, which is an indicator for the similarity of signals; for the shown graphs the normalized cross correlation at zero lag is -0.97.

However, two deviations in the shape of the curves are particularly striking: The characteristic double hump of the occurring load can not be observed in the relative movement, and the final value of the relative movement at the end of stance phase does not return to zero, even though no load is applied. Nevertheless, overall the measured and evaluated data of the relative movement are plausible.

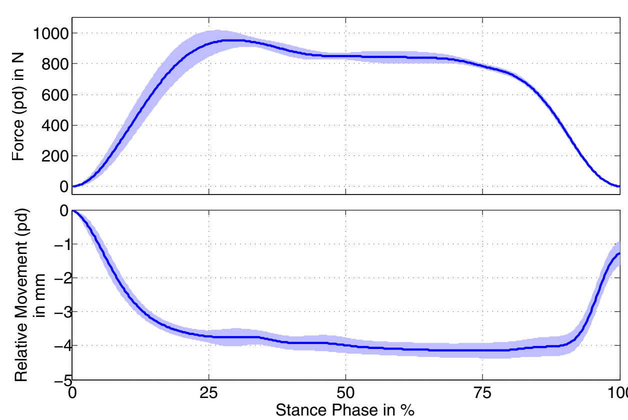

Fig. 2. Mean and standard deviation of the detected force (top) and relative movement (bottom) in the pd-direction for a walking speed of 0.85 m/s.

B. Anteroposterior Direction

Fig. 3 shows the results for the ap-direction. In contrast to the relative movement in the pd-direction, which can be clearly allocated to the applied load, the movement of the stump in the ap-direction is largely influenced by the motion sequences in the respective gait event. This observation can be explained by comparing the advancement in position of the resulting vector of the GRF, its force application point (the center of pressure (CoP)), and the center of mass (CoM) during stance phase. Fig. 4, which shows the sequence of a typical stance phase (c.f. [16]), displays the link of the three factors. The location of the CoM is approximated by the center of the triangles, which represent the beginning of the upper body. At the beginning of stance phase, during initial contact (IC), the CoM is located behind the CoP. This changes in the course of stance phase - the CoM moves over the CoP until it is finally, at toe-off (TO), spatially located in front of the CoP. At times of greatest local differences between CoP and CoM (IC and TO), the relative movement between socket and stump also reaches its maxima. The plateau of the relative movement ($20-85$ % of stance phase, cf. Fig. 3) indicates the area in which the resultant GRF vector is located close to the CoM, thus only minimal relative movement is detected. Accordingly, the relative movement in ap-direction is plausible.

C. Influence of Walking Speed

In the following, the influence of walking speed is assessed. Therefore, box plots of the data at characteristic time steps in the stance phase for the two translational degrees of freedom are displayed. In each box, the central line marks the median and the black cross represents the mean value. The edges of the box are the 25th and 75th percentiles, the whiskers extend to the most extreme data points not considered outliers, which are plotted individually.

1) Proximodistal Direction: As previously postulated, the relative movement in the pd-direction correlates with the occurring load. Among other factors, the amount of vertical GRF is influenced by walking speed [17]. Fig. 5 shows the box plot of the maximum load applied (top) and the corresponding relative movement (bottom) for each test series. Although not statistically significant, the evaluated data display a trend towards higher levels of applied load and greater relative movement with increasing gait velocity (Fig. 5), which supports the stated hypothesis about a causal correlation between applied load and level of relative movement in the pd-axis.

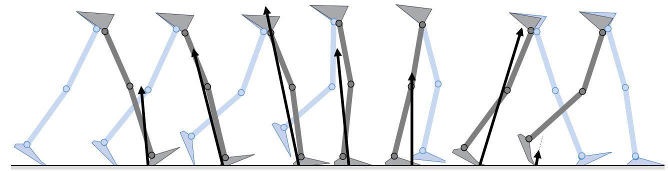

Fig. 4. Advancement of position of the resulting GRF vector, with its origin at the CoP, and CoM during a gait cycle.

2) Anteroposterior Direction: Contrary to the changes in the applied load for the pd-axis, the progression of the force curve in ap-direction does not reveal adjustments with walking speed [18]. Nevertheless, the detected relative movement changes with gait velocity, particularly at TO. Fig. 6 (top) displays the box plot of the relative movement during TO at the end of stance phase for the three test series. Similarly to the results in pd-direction, the differences of detected relative movement are not statistically significant. Nevertheless, a tendency is noticeable: with increasing gait velocity the amount of movement of the stump relative to the socket increases at TO. As explained in Sec. III-B, the relative movement in ap-direction is largely influenced by the motion sequences in the respective gait event. At TO, the distance between CoP and CoM is dominated by the orientation of the lower leg. The more acute the angle between tibia and ground, the greater the distance between CoP and CoM. Fig. 6 (bottom) displays the progression of tibia angle for the three test series; with increasing walking speed the detected tibia angle tends to become more acute at TO. Thus, the distance between CoP and CoM increases

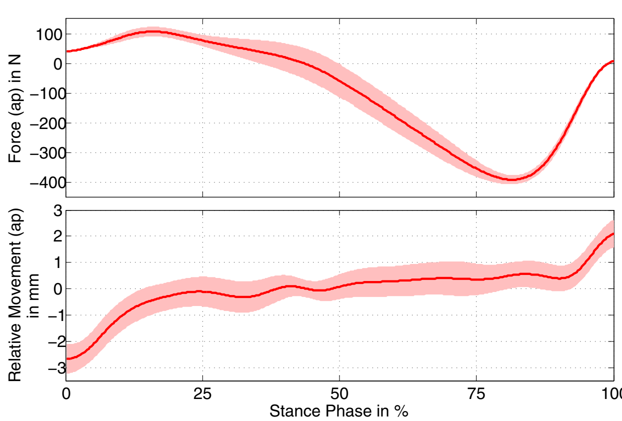

Fig. 3. Mean and standard deviation of the detected force (top) and relative movement (bottom) in the ap-direction for a walking speed of 0.85 m/s.

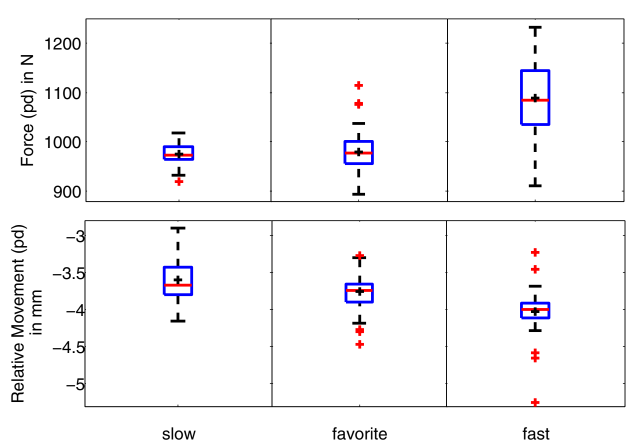

Fig. 5. Box plot for the maximum load applied (top) and corresponding relative movement (bottom) in pd-direction for the three test series.

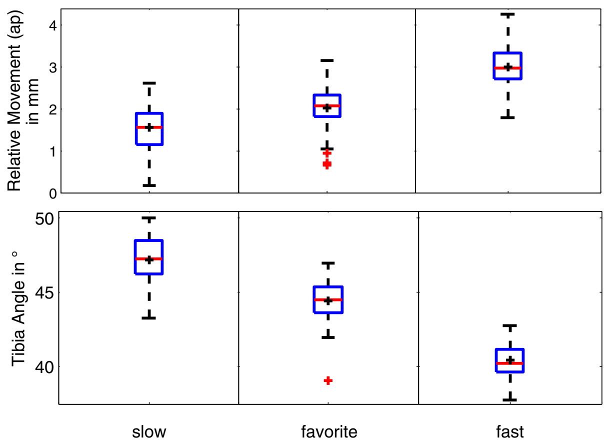

Fig. 6. Box plot for relative movement in ap-direction (top) and tibia orientation (bottom) during toe-off at the end of stance phase for the three test series.

with walking speed, which supports the hypothesis about a causal correlation between level of relative movement in ap-axis and motion sequence during gait.

IV. CONCLUSION

This study introduced a measuring approach based on motion capturing technique which enables the recording of relative movement between stump and prosthetic socket. Data of one male TT amputee for straight level walking at different gait velocities were presented. The measurement concept permits allocating the relative movement to specific gait events and applied loading conditions.

While this is the first step towards measuring the biomechanical interaction during gait, the gained insights show that usage and interpretation of motion tracking for the determination of relative movement between stump and socket entail sources of nonconformance: Tensing muscles alters the stump's structure, consequently influencing the markers position on the skin. Thus, complementing the measurements with the detection of EMG signals might be an option for further studies. As shown by [9], the relative movement between stump (skin) and socket vary with measurement point. Hence, comparability and repeatability of acquired data are challenging and have to be evaluated. Additionally, the influence of the measurement cavities in the test socket on the relative movement between stump and socket has to be assessed.

Nevertheless, the presented measuring approach revealed the causal relationships for relative movement in the sagittal plane, thus contributing to the understanding of the stump-socket interface in lower limb prostheses.

ACKNOWLEDGMENT

The acquisition of human data is conducted with consent of the Ethics Commitee of the Technical University of Darmstadt. The authors thank the subject and the prosthetist Martin Brehm (working for Sanitätshaus KLEIN, Darmstadt-Dieburg), for supporting the pilot study.

REFERENCES

[1] H. Wetz; U. Hafkemeyer; J. Wühr and B. Drerup, Einfluss des C-Leg-Kniegelenk-Passteils der Fa. Otto Bock auf die Versorgungsqualität Oberschenkelamputierter, in Orthopädie 2005, p. 298-319.

[2] D. Berry, Microprocessor Prosthetic Knees, in Physical Medicine and Rehabilitation Clinics of North America, Vol. 17, 2006, p. 91-113.

[3] A. Mak; M. Zhang and D. Boone, State-of-the-art research in lower-limb prosthetic biomechanics-socket interface: A review., in Journal of Rehabilitation Research & Development, Vol. 38 No. 2, March/April 2001, p. 161-174.

[4] G. Colombo; S. Filippi; C. Rizzi and F. Rotini, A new design paradigm for the development of custom-fit soft sockets for lower limb prostheses, in Soft Products Development, Vol. 61 No. 6, August 2010, p. 513-523.

[5] B. Klasson, Appreciation of prosthetic socket fitting from basic engineering principles, in National Centre for Training and Education in Prosthetics and Orthotics, University of Strathclyde, 1995.

[6] U. Erikson and R. Lemperg, Roentgenological study of movements of the amputation stump within the prosthesis socket in below-knee amputees fitted with a PTB prosthesis, in Acta Orthopaedica Scandinavica, Vol. 40 No. 4, 1969, p. 520-529.

[7] S. Grevsten and U. Erikson, A roentgenological study of the stump-socket contact and skeletal displacement in the PTB suction prosthesis, Upsala Journal of Medical Science, Vol. 80 No. 1, 1975, p. 49-57.

[8] M. Lilja; T. Johansson and T. Öberg, Movement of the tibial end in a PTB prosthesis socket: a sagittal X-ray study of the PTB prosthesis, in Prosthetics and Orthotics International, Vol. 17 No. 1, April 1993, p. 21-26.

[9] P. Commean; K. Smith and M. Vannier, Lower extremity residual limb slippage within the prosthesis, in Archives of Physical Medicine and Rehabilitation, Vol. 78 No. 5, May 1997, p. 476-485.

[10] M. Zhang; A. Mak and A. Chung, MRI investigation of musculoskeletal action of trans-femoral residual limb inside a prosthetic socket, in Proceedings of the 20th Annual International Conference of the IEEE Engineering in Medicine and Biology Society, Vol. 20 No. 5, 1998, p. 2741-2743.

[11] J. Sabolich, Contoured adduction trochanteric controlled alignment method (CAT-CAM): Introduction and Basic Principles, in Clinical Prosthetics & Orthotics, Vol. 9 No. 4, 1985, p. 15-26.

[12] P. Convery and K. Murray, Ultrasound study of the motion of the residual femur within a transfemoral socket during gait, in Prosthetics and Orthotics International Vol. 24 No. 3, December 2000, p. 226-232.

[13] P. Convery and K. Murray, Ultrasound study of the motion of the residual femur within a transfemoral socket during daily activities other than gait, in Prosthetics and Orthotics International Vol. 25, 2001, p. 220-227.

[14] F. Appoldt; L. Bennett and R. Contini, The results of slip measurements in above-knee suction sockets, in Bulletin of Prosthetics Research, Fall 1968, p. 106-112.

[15] J. Schuy; and S. Rinderknecht, Integrated Measurement System for Amputee Gait Analysis: A Pilot Study, in IEEE EMBC- Healthcare Innovations & Point-of-Care Technologies, 8-10 October 2014, Seattle, USA.

[16] M. Whittle, Gait analysis: an introduction. Edinburgh; New York : Butterworth-Heinemann, 2007.

[17] T. Keller; A. Weisberger; J. Ray; S. Hasan; R. Shiavi and D. Spengler, Relationship between vertical ground reaction force and speed during walking, slow jogging, and running, in Clinical Biomechanics, Vol. 11 No.5, 1996, p. 253-259.

[18] V. Noll, Konzeptentwicklung und Parameteridentifikation eines biomechanischen Modells der Stumpf-Schaft-Schnittstelle von Beinprothesen, Master Thesis, August 2014, TU Darmstadt.