RUNNING IN LOWER LIMB AMPUTEES: ADVANTAGES AND LIMITATIONS OF NEW SPORTS PROSTHETIC COMPONENTS

Thomas Schmalz[1] and Jan Sottong[2]

Ottobock Healthcare, Clinical Research & Services, Göttingen, Germany[1]
German Sport University, Cologne, Germany[2]

Until some years ago, running in lower limb amputees was basically restricted by the inadequate dimensions of available prosthetic components that usually did not allow for the adequate dynamics necessary for running at lower speeds. Newly developed prosthetic components for recreational sports have enabled a great number of lower limb amputees to participate in running as an endurance sport. The present paper compares biomechanical parameters representing the functional benefits that result from the use of these components. The results were used to define potential advantages and limitations of lower limb amputee running depending on the level of amputation. Running of TF amputees is characterised by specific constraints based on the absence of knee stabilising muscles and the technical features of prosthetic components.

KEY WORDS: Running Biomechanics, Lower Limb Amputee Running, Sports Prostheses.

INTRODUCTION: For competitive sports, especially sprinting for transtibial (TT) and transfemoral (TF) amputees (Paralympic classes T44/43 and T42), there has been continuous dynamic optimisation of prosthetic design in the last 20 years (Grobler, Ferreira & Terblanche, 2015). The development of prosthesis components, which often focused on competitive sports, led to the situation where for a long time, special components were not available for recreational sports and the growing wish of leg amputees to engage in sport as part of their rehabilitation was not adequately addressed.

In recent years, increasing activities of various manufacturers have been observed that aim to close the gap in the range of components for recreational sports by means of new innovations (Hobara et al., 2013). With this background, this study presents the results of biomechanical tests of running with prosthesis components that were developed for TT (sports foot 1E95, Ottobock) and TF amputees (sports system: 3S80 knee joint and sports foot 1E90, Ottobock) who engage in recreational sports. At the same time, in a second step, running with everyday components and the new components for recreational sports should be compared to enable the evaluation of the functional benefit for lower limb amputees resulting from these new components.

METHODS: This study included 5 male unilateral TT amputees with mobility grade 3 and 4 (44 ±12 y, 85 ±16 kg, 182 ±9 cm, amputation time 16 ±12 y). Only one amputee reported experience running with an everyday prosthetic foot. A second group of participants consisted of 9 unilateral TF amputees, also mobility grades 3 and 4 (8 male, 1 female, 39 ±10 y, 85 ±16 kg, 181 ±6 cm, amputation time 12 ±9 y). They also reported a strong interest in sports, but none of them had experience running with an everyday prosthesis. All TF amputees had been fitted with an everyday prosthesis with a microprocessor-controlled knee (C-LEG or GENIUM / GENIUM X3, Ottobock, Germany).

For comparison, 6 neurologically and orthopaedically healthy male NA were recruited (24 ±3 y, 77 ±12 kg, 180 ±7 cm).

The biomechanical tests were conducted in a gait laboratory with a 12m walkway. The kinematics of movement were recorded with an optoelectronic camera system (12 Bonita cameras, VICON, Oxford, United Kingdom; measuring frequency 200 Hz) using 17 passive markers that were positioned in accordance with a previously described, self-developed model (Schmalz, Blumentritt, Drewitz & Freslier, 2006). Ground reaction forces were measured using two force plates integrated into the walkway (9287A, KISTLER, Winterthur, Switzerland; measuring frequency 1 kHz). The external joint moments were determined using kinematic data and ground reaction forces using an algorithm described in an earlier study (Schmalz et al., 2006). The TT amputees had no previous experience with the new

1E95 sports foot. In the first step, an experienced prosthetist integrated this foot into the prosthesis system in accordance with the instructions for alignment established in an earlier study (Sottong, 2016). Then the athletes tested the system intensively for 30 to 60 min. After all preparations were finished, there was a resting phase of about 15 minutes, and the markers were positioned before starting the tests.
All TF amputees had been fitted with the sport prosthesis system between 4 and 8 weeks before the laboratory tests and used it during this period for recreational sports, including running. Thus, they had already completed a fairly long training phase at the start of the tests. For this reason, these athletes and the group of NA had only a 15-minute warmup phase after the preparations for measurements. The prosthetic alignment was adjusted according to the manufacturer's instructions (Ottobock Healthcare GmbH, 2014).
The athletes in all three groups were instructed to run several times through the measuring volume in the laboratory at a self-selected speed that should subjectively correspond to running in a natural environment. Between 6 and 10 test runs were performed during which all measurement parameters for a running cycle were recorded for the prosthesis and the contralateral side of the amputees. The values for both limbs were included in the analysis. From these values, standardised running cycle means were calculated and peaks of the biomechanical parameters were determined. Parameters that had been measured in earlier studies of the biomechanical properties of running were used for the analysis (Cavanagh, 1990; Neptune & Sasaki, 2005). For the quantitative comparative analysis, peaks of the biomechanical parameters were examined for significant differences using the Mann-Whitney U test.
For the comparison of running with the new sports prosthesis components and with everyday prostheses, one TT amputee who reported having experience running with everyday feet completed a second test series with this system (everyday foot: 1C60 Triton, Ottobock, Germany). One athlete from the group of TF amputees also tested the everyday prosthesis (GENIUM X3 prosthetic knee joint and 1C60 Triton foot, Ottobock, Germany) for running in the manner described above after a 60-minute adaptation phase.

RESULTS:

Biomechanical characteristics of running with a prosthesis

For the time-distance parameters typical for running, there were only slight differences between the three groups. The running speeds of 2.9 and 3.0 m/s correspond to running times of 5:33 min and 5:44 min per kilometer (8:56 min and 9:14 min per mile). Since these speeds are equivalent to typical "endurance running" speeds, a comparison of the biomechanical parameters can be made without taking the effect of speed into account. The mean stride lengths of between 1.08 and 1.14 m and the support times between 0.24 and 0.28 s were within the known range for NA running (Cavanagh, 1990). Only the difference of the support time for the prosthetic limb between TF and TT amputees was significant (0.24 (TF) vs. 0.27 (TT) s, $p \leq 0.05$).
For the kinetic parameters, no significant or fundamental structural differences were found for the vertical component of the ground reaction force in any of the comparisons; the maximum values were between 255% and 274% of BW. The horizontal component of the ground reaction force showed disability-specific anomalies. The maximum braking value in the first half of the support phase was reduced significantly by approx. 10% BW for both the TT and the TF amputees in comparison with NA and the respective contralateral limb. The acceleration maximum in the second part of the support phase was also significantly reduced in TT amputees. However, the corresponding value for TF amputees was of a similar order of magnitude as that of all non-amputated limbs measured. In addition, an extremely rapid transition from a braking to an accelerating effect after 12% of the running cycle was observed in these amputees. For the sagittal moment acting on the knee joint of the TF amputees, the typical flexion moment for running was not measured; an extension moment acted during the entire support phase. A significantly reduced flexion moment (-1.48 vs. -2.44 Nm/kg, $p \leq 0.05$) acted at the knee joint of the prosthetic limb of TT amputees compared with the NA. The joint moments of the contralateral limbs of amputees were comparable with those of NA. Among the kinematic characteristics of the ankle joint, dorsal extension

significantly increased by approx. 7° was measured during the support phase for the 1E95 sports foot used by the TT amputees. The kinematic parameters of the knee joint and the thigh segment of TT amputees were similar to those of NA. For the TF amputees, natural knee flexion in the support phase is not possible. The mean flexion angle of 91° in the swing phase was only slightly increased compared with the angle in NA. The movement characteristics of the thigh segment of these amputees was marked by extension starting immediately after the start of the support phase with a high speed and was followed by abnormally strong flexion in the flight and swing phases. The maximum flexion angle of 43° was significantly increased by an average of 10-13° compared with all other thigh segment movements that were analyzed.

Comparison of characteristics: running prosthesis vs. everyday prosthesis

The TT amputee with experience in running ran at a somewhat higher speed (3.1 vs. 2.9 ms) with the 1E95 sports foot than with the everyday foot and used longer stride lengths. There were striking quantitative and structural differences in the ground reaction forces measured. The maximum of the vertical component was considerably higher with the sports foot (291% vs. 257% BW), reaching nearly three times the body weight and in addition, the curve was clearly more harmonious with the sports foot, without two "peaks". When the sports foot was used, the horizontal component had reduced maximum braking forces (-12% vs. -28% BW) and increased acceleration forces (19% vs. 13% BW). There were only slight differences for the proximal joints when the two foot designs were compared. The exception was somewhat more pronounced knee extension in the late support phase with the sports foot.

For the TF amputee examined in this study, the running parameters differed considerably between the everyday prosthesis and the new sports prosthesis system. The maximum value of the vertical ground reaction force with the everyday prosthesis was increased by 36%, but an extremely rapid drop in the force was measured in the second part of the support phase. It was simultaneously observed in this interval that, unlike the sports prosthesis, only very slight accelerating forces in the direction of movement occurred with the everyday prosthesis. The maximum value of the knee extension moment was increased noticeably by around 0.4 Nm/kg with the sports prosthesis. The angles of the knee joint and the thigh segment on the prosthesis side differed considerably in the flight and swing phases. With the everyday prosthesis, an abnormally high maximum flexion angle of 120° was measured in the knee joint in the swing phase (sports prosthesis 80°). The thigh segment is initially extended by around 11° less with the everyday prosthesis compared with the sports prosthesis. In the flight and swing phases that follow, this segment is extremely strongly flexed with the everyday prosthesis. The maximum is 72°; a value of 46° is measured with the sports prosthesis.

DISCUSSION: The results of this study are suitable for classifying the biomechanical parameters of running depending on the level of leg amputation and for describing the advantages of new components specifically developed for sports prostheses.

When fitting TT amputees, only the functions of the foot and the ankle are replaced by prosthetic components. This means that both in daily routine and for sports, there is not an especially high risk of falling because, with the exception of the gastrocnemius muscle, all knee and hip muscles are nearly completely preserved for these athletes. This can be considered to be a prerequisite for the nearly natural control of the knee and hip joints when running. In fact, in comparison with the parameters for the knee and hip joints in NA, only slight differences are observed for the majority of the measurement parameters regarding joint movements and joint moments. These biomechanical properties of TT amputee running apply to both of the prosthetic feet tested in this study. However, the analysis of the ground reaction forces in particular showed considerably improved roll-over characteristics of the new sports foot.

The main problems in fitting TF amputees with prostheses are due to the complete loss of the muscles surrounding the knee. This means that the flexion moments that normally act on the knee under load become a safety concern. Because the technical solutions for this in everyday prostheses (Bellmann, Schmalz, Ludwigs & Blumentritt, 2012) are not feasible for running, running for transfemoral amputees is subject to the constraint of a permanent acting

extension moment (see also Buckley, 1999; Ojala, 2012). There are two options for complying with this constraint. First, the athlete can make the prosthetic system "safe" by developing good muscle strength in the hip extensors. Another option is to configure the prosthesis in such a way to create the conditions in which only extension moments act at the rotational axis of the knee in the support phase. Since unlike with Paralympic athletes, recreational athletes are not always able to develop sufficient strength in the hip flexors, the prosthetic configuration is very important for these runners.
The comparison between running with the everyday and the new sports components revealed considerably greater differences than in TT amputees. Although the GENIUM X3, unlike the 3S80 sports knee, implements hydraulic damping of knee flexion under load, the joint remains completely extended during the support phase. This is an evidence that the cycle of flexion and extension in the support phase in NA cannot be performed with the currently available technical solutions and that the constraint for running for TF amputees postulated above is in fact universally valid until now. It can also be concluded from the analysis of the ground reaction forces that everyday feet are not suitable for running for TF amputees. Although the comparison of running with everyday and sports components was made with only one runner each, the results show a clear trend, as the differences measured are a plausible explanation of the differences in design.

CONCLUSIONS: The results can be interpreted to be an indication that the newly developed components decisively improve the orthopaedic technology requirements for running for leg amputees. This means that many amputees can again engage in running as a sporting activity and benefit from the commonly known health effects for the neuromuscular and cardiovascular systems. The motion pattern of TT amputees is similar to that of non-amputees. Currently, in TF amputee running there is the inevitable requirement that an extension moment must act on the rotational axis of the prosthetic knee joint during the support phase. This is realised by a specific prosthetic alignment and a compensatory motion pattern.

REFERENCES:

Bellmann, Schmalz, T., Ludwigs, E., Blumentritt, S. (2012). Immediate effects of a new microprocessor-controlled prosthetic knee joint: a comparative biomechanical evaluation. *Archives of Physical Medicine and Rehabilitation*, 93, 541–549.

Buckley, J.: Sprint kinematics of athletes with lower-limb amputations (1999). *Archives of Physical Medicine and Rehabilitation*, 80, 501–508.

Cavanagh, P. (1990). Biomechanics of distance running. Champaign: Human Kinetics.

Grobler, L., Frerreira, S., Terblanche, E. (2015). Paralympic sprint performance between 1992 and 2012. *International Journal of Sports Physiology and Performance*, 10, 1052–1054.

Hobara, H., Baum, B., Kwon, H., Shim, J. (2013). Running mechanics in amputee runners using running-specific prostheses. *Japanese Journal of Biomechanics in Sports Exercise*, 17, 1–9.

Neptune, R., Sasaki, K. (2005). Ankle plantar flexor force production is an important determinant of the preferred walk-to-run transition speed. *Journal of Experimental Biolology*, 208, 799–80.

Ojala, E. (2012). Biomechanical analysis of transfemoral amputees sprint running and block start. Thesis, University of Jyväskylä.

Ottobock Healthcare GmbH (2014), Instructions for use of 3S80 – 647G813-03-1507. Ottobock Healthcare GmbH, Duderstadt.

Schmalz, T., Blumentritt, S., Drewitz, H., Freslier, M. (2006). The influence of sole wedges on frontal plane kinetics, in isolation and in combination with representative rigid and semi-rigid ankle-foot-orthoses. *Clinical Biomechanics*, 21, 255-263.

Sottong, J. (2016). Biomechanische Analyse des Laufens von Unterschenkelamputierten: Ableitung einer Aufbaurichtlinie für einen innovativen Sportprothesenfuß. Thesis, German Sports University, Cologne.