PROSTHETIC LEG DESIGN, FORCE PRODUCTION, AND CURVE SPRINT PERFORMANCE: A PILOT STUDY

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We compared the use of a running specific prosthesis (RSP) with a solid or "split-toe" design by athletes with a leg amputation on sprinting speed and stance-average centripetal ground reaction force (GRF) along a flat 400 m track curve, 200 m track curve, and straightaway. Three athletes with a right transtibial amputation performed maximal effort sprints along the curves (clockwise and counterclockwise) and straightaway of an indoor track using a traditional, solid RSP and an RSP with a split-toe design while we measured 3D GRFs and kinematics. Sprinting speed was significantly faster (p = 0.003) when using the split-toe RSP across curve conditions and directions compared to the solid RSP. However, there was no significant effect of RSP design on stance-average centripetal force (p = 0.180). Sprint speed was similar between RSP designs on the straightaway (p = 0.705).

KEYWORDS: bend, Paralympics, amputee

INTRODUCTION: For athletic track events like the 400 m sprint, more than half of the race is completed along a curve. Sprinting along a curve imposes different force production requirements (Luo & Stefanyshyn 2011) and elicits slower maximum sprinting speed compared to a straightaway (Taboga et al. 2016, Greene 1985). However, improving sprinting speed on a curve may improve overall performance in these athletic events.

Athletes with a transtibial amputation compete in sprint events with the use of a passive-elastic running-specific prosthesis (RSP) attached to their affected leg, which stores and returns mechanical energy in the sagittal plane during ground contact. RSPs are typically made with a solid piece of carbon fiber and are therefore torsionally stiff, resisting frontal plane rotation during running. Recently, Fillauer Composites (Salt Lake City, Utah, USA) manufactured an RSP with a "split-toe" design, where a distal portion of the RSP is cut longitudinally (Fig. 1). This design feature allows the medial and lateral portions of the distal RSP to bend independently and may therefore reduce torsional stiffness. Such a design could improve traction and thus centripetal force production and sprint speed along a track curve (Luo & Stefanyshyn 2011) in athletes with an amputation.

We compared maximum sprinting speed and centripetal force production of athletes with a transtibial amputation using an RSP with and without a split-toe design. We hypothesized

Figure 1. Split-toe (top) and solid (bottom) prostheses. Split-toe prosthesis differed only in the longitudinal cut on the distal end.

that sprinting speed would be faster using the split-toe RSP than the solid RSP on curves and that sprinting speed would be similar between RSP designs on the straightaway. An increase in mean sprinting speed for a given curve radius could be accomplished through an increase in stance-average centripetal force (mv^2/r). Thus, we hypothesized that participants would elicit greater affected leg stance-average centripetal ground reaction forces (GRFs) on a curve when using the split-toe compared to solid RSP.

METHODS: Three individuals (2 males: 26.4 s and 21.9 s 200m PB, 1 female: 29.5 s 200m

PB; mean ± SD mass: 72.92 ± 10.72 kg; height: 1.80 ± 0.06; age: 25 ± 9) with a right transtibial amputation participated in this study. All participants had at least one year of experience competing using an RSP and reported running at least 3 days per week over the 6 months prior to data collection. All participants had competed in a sprint event (400 m or shorter) within the past two years. The protocol was approved by the University of Colorado Boulder Institutional Review Board and all participants provided informed consent prior to participation.

The split-toe and solid RSP were made of carbon fiber and had identical shapes, height, and sagittal plane stiffness, but the split-toe RSP was cut longitudinally on the distal end (Figure 1). The cut allowed the medial and lateral sides of the RSP to bend independently. All RSPs were manufactured by Fillauer Composites, were mounted posteriorly to each participant's socket, and had a stiffness category recommended based on each participant's mass.

Participants completed a randomized series of 40 m sprints on a flat indoor track using the split-toe and solid RSP. We instructed participants to run at their maximal effort for each trial and provided at least 8 minutes of rest between trials. Participants performed clockwise and counterclockwise sprints along curves with radii of 36.5 m and 17.2 m, representative of the innermost lane of a 400 m and 200 m track, respectively. They also sprinted along a 40 m straightaway. Participants practiced running in each condition and adjusted their starting position to allow them to achieve maximum curve sprinting speed halfway along the curve. Athletes ran over two adjacent force plates (1000 Hz, 1.2 m x .6 m; AMTI, Watertown, MA, USA) embedded in the ground and covered with an indoor track surface that was level with the surrounding surface. We recorded 3-dimensional kinematics using 10 high-speed motion capture cameras (200 Hz, Vicon, Oxford, UK). The force plates and capture volume were located halfway along the runway. Trials were repeated until athletes successfully landed on the force plates at least once. Participants were not blinded to the RSP designs.

Three-dimensional GRFs and kinematic marker position data were filtered with 4th order zero-lag low pass Butterworth filters with a 45 Hz cutoff. We measured sprinting speed using average pelvis marker velocity, which we calculated using markers located bilaterally on the iliac crests, anterior superior iliac spines, and posterior superior iliac spines. Sprinting speed was averaged over the length of the capture volume (~5 m). We calculated stance-average centripetal force relative to the local coordinate system of the force plate for the affected leg as the mean centripetal force measured over stance phase, which was identified using a 5 N vertical GRF threshold.

Data analysis was performed using custom MATLAB (Mathworks, Natick, MA, USA) (Alcantara, 2019) and R scripts (R v3.6.1). We constructed linear mixed-effects models (α = 0.05) to determine the effect of RSP design on maximum sprinting speed and force production. Factored fixed effects included curve condition (200 m & 400 m track curves), direction (clockwise & counterclockwise), and RSP design (split-toe & solid).

RESULTS: Mean (± SE) sprinting speed was significantly affected by curve condition (p <0.001), running direction (p < 0.001), and RSP design (p = 0.003), with the split-toe RSP increasing maximum sprint speed by 0.13 ± 0.04 m/s compared to the solid RSP for a given curve condition and direction (Fig. 2). Sprinting speed was 0.31 ± 0.04 m/s faster in the 400 m track curve condition compared to the 200 m track curve. Sprinting speed was 0.35 ± 0.04 m/s slower when running in the clockwise compared to counterclockwise direction. Using the split-toe RSP did not significantly affect sprinting speed on the straightaway compared to the solid RSP (p = 0.705).

Stance-average centripetal GRF for the affected leg was significantly affected by curve condition (p < 0.001) and sprinting speed (p < 0.001), but not RSP design (p = 0.180) or running direction (p = 0.746). Mean stance-average centripetal GRF for the affected leg on the 200 m track curve was 0.43 BW and decreased to 0.19 ± 0.02 BW in the 400 m track curve condition

for both curve directions. When controlling for speed and curve condition, participants produced similar stance-average centripetal GRFs in their affected leg when running with the RSP on the inside (clockwise direction) and outside of the curve (counterclockwise direction).
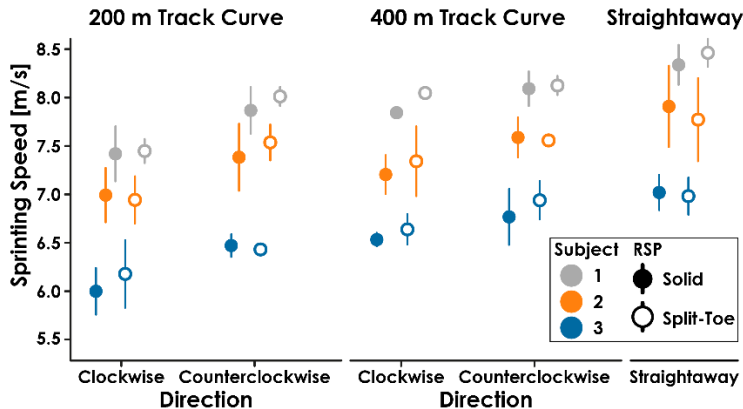

Figure 2. Mean ± SD maximum sprinting speed across subjects and conditions. Sprinting speed using the split-toe running-specific prosthesis (RSP) was faster than the solid RSP across curve conditions and directions, but similar during the straightaway. Speed was slower when sprinting in the clockwise compared to counterclockwise direction and faster with increased curve radius.

DISCUSSION: The data support our first hypothesis that maximum sprinting speed on curves would be faster when athletes used the split-toe RSP compared to the solid RSP but similar on the straightaway. On average (± SE), participants ran 0.13 ± 0.04 m/s faster using the split-toe RSP for a given direction and curve condition (Fig. 3). Centripetal GRF should presumably increase with a faster speed during running on a curve with the same radius. However, the data did not support our second hypothesis because there were no statistically significant differences in centripetal GRF for the affected leg between RSP designs. Two of three athletes had greater affected leg stance-average centripetal GRFs when using the split-toe RSP compared to the solid RSP across curve conditions and running directions (Fig. 3).

For an object rotating about a point, the centripetal (radial) force, Fc, experienced by the object is described as: $mv^2/r = Fc$, where m is body mass, v is tangential velocity, and r is curve radius. Thus, sprinters running on a curve must apply Fc to stay within their lane and achieve the fastest speed. We observed statistically significant increases in sprint speeds using the split-toe compared to solid RSP, but no statistically significant change in affected leg centripetal GRF. Considering the equation for Fc, different sprinting speeds and similar amounts of Fc production when using different RSP designs could be achieved by decreasing the curve radius. Although participants ran along curves with radii of 36.5 m and 17.2 m, the 1.22 m lane width allows athletes to vary their path traveled for a given curve condition while still accomplishing the task. We measured the actual radius of the curve traveled by participants (effective curve radius) across conditions by fitting a circle to the average pelvis marker trajectory for every trial and calculating the circle's radius. We then constructed a linear model to determine if there was an effect of RSP design on effective curve radius. This model revealed that there was no significant effect of RSP design (p = 0.481) or running direction (p = 0.981) on effective curve radius, suggesting that participants did not vary their trajectory according to the RSP they were using or direction they were sprinting. We found that mean (± SE) effective curve radius for the 400 and 200 m track curve conditions were 39.80 ± 0.28 m and 18.14 ± 0.05 m, respectively. Although only 1-3.3 m greater than the radii of the 400 and 200 m track curve conditions, it is possible that small changes in both affected leg centripetal GRF and effective curve radius contributed to the overall change in sprinting speed. Moreover, we did not compare unaffected leg centripetal GRFs. It is possible the unaffected leg centripetal GRFs may contribute to speed differences between RSP designs. However, further research is required to understand how use of different RSP designs affects centripetal force production in both legs across curve radii with additional subjects.

While we were unable to identify the underlying mechanism responsible for changes in sprinting speed, our findings suggest curve sprint performance could be improved by using an RSP with a split-toe design. For example, we estimate that for a sprinter with a transtibial amputation and a 400 m personal best of 50 s (current world record is 49.66), using the split-toe RSP would reduce the time spent on the curve by 0.54 s (1.8%). This represents a

substantial improvement in performance, as races are often decided by a fraction of a second.

We only tested participants with a right leg transtibial amputation, but by having participants run along curves in the clockwise and counterclockwise directions, we were able to test the effect of having the split-toe RSP on the inside versus outside of the curve. Our findings suggest that although there was a decrease in speed for athletes sprinting clockwise around a curve compared to running on a counterclockwise curve, using the split-toe RSP still resulted in faster sprinting speeds compared to the solid RSP. This also suggests that athletes with a left leg transtibial amputation could benefit from using an RSP with a split-toe design on a curve.

The number of participants in this study is a potential limitation. Also, we were unable to blind participants to the RSP they were using for a given trial. While we provided the same instructions to participants to sprint at maximal effort for all trials, participants may have been biased to run faster in the split-toe RSP. However, such bias would not explain why participants ran faster on a curve with the split-toe RSP and not on the straightaway. Measures of centripetal force were relative to the local coordinate system of the force plate. This may have introduced error if the orientation of the foot during stance phase was tangential to the curve but not orthogonal to the force plate. However, the large radii of the curves tested minimizes the effect of this error, as the tangent of the curve rotates ≤ 2° over the length of a force plate. Future studies are planned to determine the underlying reasons for faster curve-running when subjects with a transtibial amputation use an RSP with a split-toe versus a solid design.
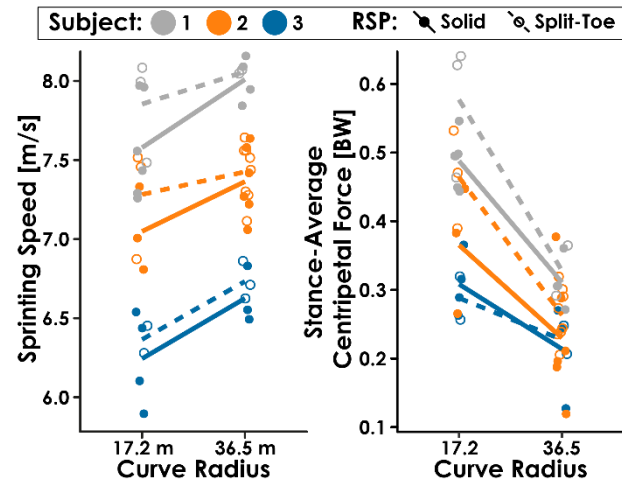

Figure 3. Sprinting speed and affected leg stance-average centripetal force across subjects and curve conditions (both running directions combined). Subjects ran faster on the curve using the split-toe running-specific prosthesis (RSP) than the solid RSP and two subjects produced greater affected leg stance-average centripetal force using the split-toe RSP than the solid RSP across curve conditions and running directions.

CONCLUSION: We investigated the effects of athletes with a transtibial amputation using an RSP with a split-toe and solid design on sprinting speed and affected leg centripetal force production along curves with different radii and the straightaway of a track. We found that curve sprinting speed was faster when athletes used the split-toe RSP compared to the solid RSP, but there were no statistical differences in affected leg stance-average centripetal force or effective curve radius between the two RSP designs. Use of both RSPs resulted in similar sprinting speeds along the straightaway. Sprinters with a unilateral transtibial amputation may be able to achieve faster curve sprinting speeds with the use of an RSP with a split-toe design compared to a traditional, solid RSP.

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