The effects of changes in the sagittal plane alignment of running-specific transtibial prostheses on ground reaction forces

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Abstract. [Purpose] To verify the effects of sagittal plane alignment changes in running-specific transtibial prostheses on ground reaction forces (GRFs). [Subjects and Methods] Eight transtibial amputees who used running-specific prostheses during sprinting participated. The sprint movements were recorded using a Vicon-MX system and GRF measuring devices. The experiment levels were set as regularly recommended alignment (REG; the normal alignment for the subjects) and dorsiflexion or plantar flexion from the REG. [Results] The subjects were classified into fast (100-m personal best < 12.50 s) and slow (100-m personal best ≥ 12.50 s) groups. In both groups, there were no significant differences in the center of gravity speed; further, the difference in the stance time was significant in the slow group but not in the fast group. Significant differences were observed in the step length for the fast group, whereas the stance time and step rate significantly differed in the slow group. The GRF impulse showed significant differences in the vertical and braking directions in both groups. [Conclusion] The GRFs are affected by sagittal plane alignment changes in running-specific prostheses. Moreover, our results suggest that the change in GRFs along with the altered sagittal plane alignment influenced the step length and step rate.

Key words: Transtibial amputee, running-specific prosthesis, ground reaction force

INTRODUCTION

Studies on able-bodied runners have been conducted from various viewpoints including kinematics of the lower limb joint angles and changes in angular speed1-2, kinetics of ground reaction forces (GRFs) and joint torque3, and physiological aspects such as the muscular activities of lower limbs4. Recently, there have been an increasing number of studies on amputee sprinters. Prince5 examined the characteristics of 9 transtibial amputees, including the peak values of the GRF and impulse. According to their study, the impulse expressed the difference between the sound foot and the prosthetic foot better than the peak value, and the asymmetry varied depending on the properties of the foot section of the prosthetic. Grabowski6 examined bilateral amputee sprinters and reported that the GRFs needed to maintain maximum speed when using running-specific transtibial prostheses were significantly smaller than those needed by able-bodied runners. Brüggemann et al.7 and Weyand et al.8 reported that improving the GRF value of prostheses contributed to improving the performance of amputee sprinters. In addition, Grabowski8 reported a relationship between impulse and step rate; they found that running at a high step rate could be achieved by reducing the impulse in the vertical direction while sprinting at one’s maximum speed. However, to date, there have been no reports comparing GRF, step rate, and step length during running between amputee sprinters at low and high competition levels, and we speculate that the knowledge necessary for improving running performance can be obtained by elucidating the characteristics of high competition level-amputee sprinters.

The recent improvements in the competitiveness of amputee sprinters are remarkable, with the world records (as of April 18, 2014) for track and field sports (T43 class) being 10.57 s for 100 m, 20.66 s for 200 m, and 45.39 s for 400 m. Amputee sprinters exceed the range of disabled athletes and are catching up with general athletes. It is obvious that extensive adjustments in the running-specific prostheses will need to occur in order to keep up with the high competitiveness of amputee sprinters. Accordingly, one report indicated the possibility that the maximum sprint speed can be improved considerably depending on the length and properties of the prosthesis9. One such property is the alignment of the running-specific prosthesis; therefore, altering the alignment...
of running-specific prostheses may help improve running performance through the modulation of GRF during running. Accordingly, the purpose of this study was to elucidate the effects of changes in the sagittal plane alignment of running-specific prostheses on the GRF, step length, and step rate in transtibial amputee sprinters. We hypothesized that changes in the sagittal plane alignment of the running-specific transtibial prosthesis will lead to changes in the GRF. Furthermore, we also hypothesized that the stance time, step rate, and step length would change upon altering the alignment.

SUBJECTS AND METHODS

Subjects
Eight unilateral transtibial amputees participating in track and field sports using special prosthetic feet for running (7 males, 1 female) were included in the study. None of the test subjects had amputated legs due to angiogenic diseases or had an abnormality in the stump skin. All participants belonged to club teams for track and field sports and were training regularly. Their 100-m personal best (PB) ranged between 12.30 and 17.90 s (mean ± standard deviation, 14.85 ± 2.31 s). The analysis was conducted by dividing the test subjects into fast (100-m PB < 12.50 s) and slow groups (100-m PB ≥ 12.50 s) to reduce the influence of speed on GRF, owing to the fact that the GRF, the main outcome measure of this study, influences the running speed. The subjects were divided into 2 groups according to their running performance to reduce the influence of the speed on GRF. In addition, the cutoff of 12.50 s was based on the Paralympics participation “B” standard record.

The physical characteristics of the participants are shown in Table 1. The running-specific prosthetic feet were the Cheetah (Össur, Reykjavik, Iceland) in 2 subjects, Flex-Run (Össur) in 2 subjects, and KATANA (IMASEN Engineering Corp., Kakamihara, Japan) in the remaining 4 subjects. Furthermore, participants 4 and 8 ran by attaching the Flex-Run to their daily prosthesis socket to form a transtibial prosthesis (Table 1). Consent was obtained from each participant after explaining the purpose of the study and the risks that may be involved. This study was approved by the Research Ethics Committee, Faculty of Health and Sports Science, Juntendo University (JUSE 25-20) and complied with the guidelines set out in the Declaration of Helsinki (1983).

Methods
The experiment was conducted on a straight indoor 15-m track after the subjects had warmed up sufficiently. They rested briefly between the trials, as needed, in order to eliminate the effects of fatigue. Reflective markers were attached to the participants on the top of the head, shoulders, elbows, hands, hip joints, heels, and toes, as well as on the inside and outside of the knees, feet, and metacarpophalangeal joints. Further, markers were placed on the prosthetic socket, at a position corresponding to the underlying knee center, on the carbon-fiber foot keel, either at the same height as the lateral malleolus of the intact limb when standing on tip-toe or on the top surface of the keel, 2 cm proximal to the most distal point. For the experiment, a 3-dimensional optical position measuring instrument (Vicon-MX series T10 camera system; Vicon Motion Systems, Los Angeles, CA, USA) was used to record the sprint movements within the analysis block at a sampling frequency of 250 Hz. The GRFs during the foot contact time were also measured using 4 GRF measuring devices (40 cm × 60 cm, BP400600-2000; Advanced Mechanical Technology, Inc., Watertown, MA, USA) at a sampling frequency of 1,000 Hz. The data for body coordinates and GRF while sprinting were synchronized within the Vicon system using synchronous signals. Three experiment levels were set up by plantarflexing or dorsiflexing the running-specific prosthetic feet: the regularly recommended alignment (REG), defined as the normal alignment for a test subject; a level of 4° dorsiflexion from REG (DOR); and a level of 4° plantar flexion from REG (PLA). (Fig. 1). The subjects performed approximately 10 trials for each condition. Data from the trials in which the prosthetic

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**Table 1. Characteristics of the participants**

<table>
<thead>
<tr>
<th>Gender (M/F)</th>
<th>Age (years)</th>
<th>Height (m)</th>
<th>Total Mass (kg)</th>
<th>Stump Length (cm)</th>
<th>Mass (kg)</th>
<th>RSP (model)</th>
<th>100 m PB (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M</td>
<td>48</td>
<td>1.67</td>
<td>81.9</td>
<td>12.5</td>
<td>1.7</td>
<td>Cheetah</td>
<td>12.30</td>
</tr>
<tr>
<td>Fast</td>
<td>M</td>
<td>43</td>
<td>1.62</td>
<td>65.0</td>
<td>15.2</td>
<td>1.517</td>
<td>12.36</td>
</tr>
<tr>
<td>Slow</td>
<td>M</td>
<td>27</td>
<td>1.70</td>
<td>60.0</td>
<td>14.5</td>
<td>1.664</td>
<td>12.43</td>
</tr>
<tr>
<td>M</td>
<td>44</td>
<td>1.78</td>
<td>75.9</td>
<td>17.0</td>
<td>1.143</td>
<td>Flexrun</td>
<td>14.28</td>
</tr>
<tr>
<td>Slow</td>
<td>M</td>
<td>49</td>
<td>1.70</td>
<td>63.0</td>
<td>32.5</td>
<td>1.932</td>
<td>15.80</td>
</tr>
<tr>
<td>Slow</td>
<td>F</td>
<td>50</td>
<td>1.61</td>
<td>52.5</td>
<td>13.5</td>
<td>1.51</td>
<td>16.51</td>
</tr>
<tr>
<td>Slow</td>
<td>M</td>
<td>38</td>
<td>1.72</td>
<td>92.0</td>
<td>17.4</td>
<td>1.795</td>
<td>17.20</td>
</tr>
<tr>
<td>Slow</td>
<td>M</td>
<td>21</td>
<td>1.80</td>
<td>60.0</td>
<td>10.0</td>
<td>1.501</td>
<td>17.90</td>
</tr>
</tbody>
</table>

Average 40.0 1.70 68.8 16.6 1.595 14.85
SD 10.7 0.07 13.2 6.9 0.238 2.31
Maximum 50.0 1.80 92.0 32.5 1.932 17.90
Minimum 21.0 1.61 52.5 10.0 1.143 12.30

RSP: Running-specific prostheses

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**Fig. 1. The experimental levels**

Three levels were set up by plantarflexing and dorsiflexing the special foot section of the prosthesis for running: the regularly recommended alignment (REG), defined as the normal alignment for a test subject; a level of 4° dorsiflexion from REG (DOR); and a level of 4° plantar flexion from REG (PLA).
The differences between the levels were examined by one-way analysis of variance (ANOVA). If the p value was considered significant upon one-way ANOVA, the Tukey’s multiple comparison test was used to examine the differences in the average values. In all tests, a significance level smaller than 5% (p < 0.05) was considered significant. The statistical calculations were conducted using the JMP version 10.0.2 (SAS Institute Inc., Cary, NC, USA).

RESULTS

Tables 1–3 show the analyzed outcomes for the fast (100-m PB < 12.50 s) and slow groups (100-m PB ≥ 12.50 s). Sample data of the waveforms and analysis of the investigated parameters are shown in Fig. 2. No significant differences were observed in either group in terms of the COG speed. On the other hand, significant differences were observed in the step length for the fast group and for the stance time and step rate in the slow group. Moreover, significant differences were observed in some GRF parameters for the fast group, while only the peak values and average values of GRF significantly differed in the slow group. With regard to the impulse, significant differences were observed in the vertical direction for both groups; however, no significant differences were seen in the fast group in terms of the direction of propulsion or stance time, whereas these significantly differed in the slow group.

\[
\text{Impulse}_\text{v} = \int_{0}^{t_c} F_v dt \quad (1)
\]

\[
\text{Impulse}_\text{h} = \int_{0}^{t_c} F_h dt \quad (2)
\]

Table 2. The effect of alignment changes on the COG velocity, stance time, step length, and step rate (fast group vs. slow group)

<table>
<thead>
<tr>
<th></th>
<th>COG velocity (m/s)</th>
<th>Stance time (s)</th>
<th>Step length (m)</th>
<th>Step rate (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fast</td>
<td>DOR (n=27)</td>
<td>6.06 ±0.17</td>
<td>0.14 ±0.01</td>
<td>1.69 ±0.10</td>
</tr>
<tr>
<td></td>
<td>PLA (n=22)</td>
<td>6.18 ±0.17</td>
<td>0.14 ±0.01</td>
<td>1.78 ±0.08*</td>
</tr>
<tr>
<td></td>
<td>REG (n=25)</td>
<td>6.07 ±0.22</td>
<td>0.14 ±0.01</td>
<td>1.75 ±0.07</td>
</tr>
<tr>
<td>Slow</td>
<td>DOR (n=47)</td>
<td>5.46 ±0.61</td>
<td>0.17 ±0.01</td>
<td>1.47 ±0.16</td>
</tr>
<tr>
<td></td>
<td>PLA (n=43)</td>
<td>5.51 ±0.35</td>
<td>0.16 ±0.01*</td>
<td>1.46 ±0.17</td>
</tr>
<tr>
<td></td>
<td>REG (n=49)</td>
<td>5.53 ±0.51</td>
<td>0.16 ±0.01</td>
<td>1.50 ±0.15</td>
</tr>
</tbody>
</table>

*: p<0.05

The number of samples was a total of the trials that each subject performed for each condition.

Table 3. The effect of alignment changes on the ground reaction forces (fast group vs. slow group)

<table>
<thead>
<tr>
<th></th>
<th>Vertical</th>
<th>Braking</th>
<th>Propulsive</th>
<th>Impulse</th>
<th>Vertical</th>
<th>Braking</th>
<th>Propulsive</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fast</td>
<td>DOR (n=27)</td>
<td>2.846 ±0.290</td>
<td>−0.374 ±0.100</td>
<td>0.303 ±0.087</td>
<td>2.41 ±0.013</td>
<td>−0.011 ±0.005</td>
<td>0.015 ±0.005</td>
</tr>
<tr>
<td></td>
<td>PLA (n=22)</td>
<td>2.685 ±0.188</td>
<td>−0.319 ±0.062</td>
<td>0.312 ±0.086</td>
<td>2.22 ±0.017*</td>
<td>−0.006 ±0.006</td>
<td>0.016 ±0.004</td>
</tr>
<tr>
<td></td>
<td>REG (n=25)</td>
<td>2.825 ±0.235</td>
<td>−0.370 ±0.132</td>
<td>0.317 ±0.082</td>
<td>2.24 ±0.024</td>
<td>−0.011 ±0.009*</td>
<td>0.017 ±0.005</td>
</tr>
<tr>
<td>Slow</td>
<td>DOR (n=47)</td>
<td>2.529 ±0.246</td>
<td>−0.357 ±0.069</td>
<td>0.260 ±0.077</td>
<td>2.25 ±0.032</td>
<td>−0.013 ±0.007</td>
<td>0.016 ±0.005</td>
</tr>
<tr>
<td></td>
<td>PLA (n=43)</td>
<td>2.293 ±0.275*</td>
<td>−0.302 ±0.070*</td>
<td>0.268 ±0.064</td>
<td>0.230 ±0.027*</td>
<td>−0.007 ±0.004*</td>
<td>0.019 ±0.006*</td>
</tr>
<tr>
<td></td>
<td>REG (n=49)</td>
<td>2.487 ±0.259</td>
<td>−0.355 ±0.055*</td>
<td>0.272 ±0.083</td>
<td>0.246 ±0.033</td>
<td>−0.011 ±0.005*</td>
<td>0.017 ±0.005</td>
</tr>
</tbody>
</table>

*: p<0.05

The number of samples was a total of the trials that each subject performed for each condition.

The coordinates for each joint and the body’s center of gravity (COG) were calculated based on the positions of the body markers obtained by the Vicon system. The coordinate data for 250-Hz were smoothed with a cutoff frequency of 8 Hz\(^{(2)}\) using a quaternary low-pass digital filter\(^{(3)}\). The GRF data at 1,000 Hz were subjected to residual analysis and smoothed with a cutoff frequency of 30 Hz using a quaternary low-pass digital filter\(^{(2)}\).

The running speed was considered to be the maximum speed for the body’s COG during the stance phase on the prosthetic side. Based on the GRF measured, the time at which ground contact began was set as zero, and the time at which it ended was set as \(T_{\text{contact}}\). The step length was defined as the distance from the tip toe of the prosthetic foot to the heel marker of the sound foot. The step rate was calculated based on the time of initial contact of the sound leg from the toe off of the prosthetic foot. The maximum values were calculated for the horizontal GRF (Fy) and vertical GRF (Fz) during the foot contact time. Subsequently, the formulas below were used to calculate the impulse for the GRF, and its horizontal (\(\text{Impulse}_\text{v}\)) and vertical components (\(\text{Impulse}_\text{h}\)).

\[
\text{Impulse}_{\text{h}} = \int_{t_c} T F_h dt
\]

\[
\text{Impulse}_{\text{v}} = \int_{t_c} T F_v dt
\]
Fig. 2. Analysis of parameters
A indicates the maximum value of the ground reaction force in the vertical direction. B indicates the impulse for the ground reaction force in the vertical direction. C indicates the maximum value of the ground reaction force in the braking direction. D indicates the impulse for the ground reaction force in the braking direction. E indicates the maximum value of the ground reaction force in the direction of advancement. F indicates the impulse for the ground reaction force in the direction of advancement.

DISCUSSION

The purpose of this study was to elucidate the effects of changes in the sagittal plane alignment of running-specific prostheses on GRF in transfemoral amputee sprinters. Eight participants were instructed to sprint with 3 different alignments. The analysis was conducted by dividing the test subjects into fast (100-m PB < 12.50 s) and slow groups (100-m PB ≥ 12.50 s); while significant differences were observed only in some parameters in the fast group, differences in numerous parameters were seen in the slow group. Importantly, significant differences were observed with regard to the impulse in the vertical and horizontal directions in both groups (Table 3). These findings indicated that the GRFs are affected by changes in the sagittal plane alignment of running-specific transfemoral prostheses, thus partly supporting our hypothesis in terms of the GRF.

Generally, the running speed of an able-bodied sprinter is determined by the product of the step rate (the number of steps per unit) and step length; therefore, either or both the step rate or step length must be increased in order to increase the running speed. In previous studies on able-bodied sprinters running by varying condition of running speeds13–18, it was found that the running speed increased as the step length increased when the running speed was low, and the running speed increased as the step rate increased when the running speed was high. Since the impulse is the value obtained by integrating force with time, the impulse and step length increase as a result of an increase in the stance time with the ground, even if the force applied against the ground is minimal. Meanwhile, the stance time and swing time need to be reduced in order to increase the step rate, because the step rate size is determined by the sum of the stance time and swing time. Thus, while an increase in stance time leads to an increase in step length, it has a negative effect on the step rate. In other words, there is a negative correlation between step rate and step length. It is obvious that a human should sprint with the optimal combination of a high step rate and large step length in order to achieve a high running speed19; therefore, it is assumed that changing either the step rate or step length (or both) contributes to an increase in running speed.

Since changes were observed in the impulse in both the vertical and horizontal directions for the GRF in both groups in this study, this indicates that the changes in alignment affected the step length. Hunter et al.20 indicated that the horizontal impulse affects the horizontal moving distance for the COG during the swing phase, which comprises step length. Indeed, the step length increased in the fast group during the PLA condition in this study, and we speculate that this was caused by the reduction of the braking force during the PLA condition.

Grabowski6 demonstrated the relationship between impulse and step rate, and reported that running at a high step rate could be achieved by reducing the impulse in the vertical direction during high-speed sprinting. In the present study, an increase in the step rate was observed in the slow group during the PLA condition, indicating that changes in alignment affect the step rate. Moreover, a decrease of the impulse in the vertical direction was observed during the PLA condition, and this result corresponds with that of Grabowski’s study. Altering alignment might reduce the vertical impulse during stance, and we speculate that this is caused by reductions of the stance time during the PLA condition. As a result, a higher step rate might increase the top speed by reducing the required vertical impulse during stance, thereby supporting our hypothesis in terms of the step length and step rate.

However, the results of the present study in terms of the COG speed were not statistically significant (Table 2), likely owing to the fact that the GRF measuring devices were located at a 10-m distance from the starting point. Therefore, it is thought that a difference did not emerge due to the speed of running, and one of the limitations of this study is that the measured running distance was only 15 m, which is relatively short and corresponds only to the acceleration aspect of a 100-m sprint. To address this issue, we plan to conduct a future study with a longer running distance and to examine the kinematics and kinetics of alignment changes in each aspect of a 100-m sprint.

In conclusion, the GRF is affected by changes in the sagittal plane alignment in running-specific prostheses. At the same time, an increase in step length along with reductions of the braking impulse were observed in the fast group with a high level personal-record in the 100-m sprint. In the slow group, an increase in the step rate was observed along with reductions of the braking impulse and stance time.

REFERENCES