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ORIGINAL ARTICLE

Spatiotemporal parameters in sprinters with unilateral and bilateral transfemoral amputations and functional impairments

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Abstract

Purpose Although sprinters with unilateral (UTF) and bilateral transfemoral (BTF) amputations and functional impairments (FIs) without amputation were allocated into different classifications because of the recent revision of the International Paralympic Committee Athletics Rules and Regulations, it is unclear whether running mechanics differ among the three groups. The aim of this study was to investigate the differences in the spatiotemporal parameters of the three groups during 100-m sprint in official competitions.

Methods Using publicly available Internet broadcasts, we analyzed 11 elite-level sprinters with UTF amputation, 4 sprinters with BTF amputation, and 5 sprinters with FI without amputation. The best personal times for nearly all individuals were included. For each sprinter's race, the average speed, step frequency, and step length were calculated using the number of steps in conjunction with the official race time.

Results Although there were no significant differences in the average speed among the UTF, BTF, and FI groups (7.95 ± 0.22, 7.90 ± 0.42, and 7.93 ± 0.14 m/s, respectively, $p = 0.87$), those with BTF amputation showed significantly lower step frequency (UTF: 4.20 ± 0.20 Hz, BTF: 3.71 ± 0.32 Hz, FI: 4.20 ± 0.10 Hz, $p < 0.05$) and longer step length (UTF: 1.90 ± 0.08 m, BTF: 2.14 ± 0.02 m, FI: 1.89 ± 0.06 m, $p < 0.05$) than the other two groups.

Conclusion These results suggest that the step characteristics during sprinting are not the same among sprinters with UTF amputation, BTF amputations, or FI without amputations.

Keywords Running-specific prostheses · Paralympics · Athletics · Classification · Amputees

Abbreviations

BTF	Bilateral transfemoral
ES	Effect size
FI	Functional impairments
f_{step}	Average step frequency
L_{step}	Average step length
Lf_{ratio}	Step length/step frequency ratio
N_{step}	Number of steps
S_{100}	Average speed
t_{race}	Official race times
UTF	Unilateral transfemoral

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Introduction

Paralympic classifications for track events in athletics are generally based on sex, level of amputation, and/or similar levels of activity limitations due to disabilities. For example, prior to 2018, athletes with single unilateral transfemoral (UTF) amputation and those with all other impairments that were thought to be comparable to athletes with UTF amputation were classified into the T42 class [International Paralympic Committee (IPC) Athletics Rules and Regulations 2016–2017], which also included athletes with limb deficiency, leg length difference, impaired muscle power, and impaired passive range of movement in the lower limbs (without leg amputation). Consequently, the previous T42 class included athletes with

UTF amputation, bilateral transfemoral (BTF) amputation, and functional impairments (FIs) without leg amputations. Although each population is now allocated into a different classification because of the recent revision of the IPC Athletics Rules and Regulations (as of January 1, 2018; T42 for FI, T61 for BTF, and T63 for UTF), it is unclear whether running mechanics differ among the three groups. An increased understanding of running mechanics in these populations will provide a basis for better evaluating assistive technology that accompanies training methods and to develop evidence-based classification system in Para sport.

Theoretically, the average speed during a 100-m sprint (S_{100}) is the product of the average step frequency (f_{step}) and average step length (L_{step}). Although both parameters are inversely correlated, an increase in one factor will result in an improvement in sprint speed, as long as the other factor does not undergo a proportionately similar or larger decrease. According to previous studies, spatiotemporal patterns during walking vary with amputation levels and FIs (Eke-Okoro 1999; Javis et al. 2017). The Lf_{ratio}, which is the ratio of L_{step}–f_{step}, is a simple and quantitative index with which one can assess a deviation from a particular gait pattern (Sekiya and Nagasaki 1998). Furthermore, previous studies have demonstrated that Lf_{ratio} is useful for describing pathological gait (Eko-Okoro 1999; Rota et al. 2011; Howard et al. 2013), predicting falls in the elderly (Barak et al. 2006; Egerton et al. 2011; Callisaya et al. 2012), and better understanding the neurocontrol of gait (Egerton et al. 2011; Rota et al. 2011). However, little is known about these spatiotemporal parameters in sprinters with UTF amputation, BTF amputation, or FI without amputation.

The aim of this study was to investigate the spatiotemporal parameters in sprinters with UTF amputation, BTF amputation, or FI without amputation during a 100-m sprint. A recent study demonstrated that athletes with BTF amputation exhibited lower f_{step} but longer L_{step} than athletes with UTF during 200-m sprint (Hobara et al. 2018). Further, knee joint function is crucial for the stance and swing phase during sprinting (Kuitunen et al. 2002; Nagahara et al. 2017), indicating that loss of unilateral knee power would induce comparable activity limitation between sprinters with UTF amputation and those with FI without amputation. Therefore, we hypothesized that athletes with BTF amputation would exhibit lower f_{step} but longer L_{step} than athletes with UTF or FI during 100-m sprint.

Methods

Data collection

We analyzed 11 elite-level sprinters with UTF amputation, 4 sprinters with BTF amputation, and 5 sprinters with FIs without amputations from publicly available Internet broadcasts (YouTube; https://www.youtube.com/). These races included several Paralympic Games, the IPC World Para Athletics Championships, World Para Athletics Junior Championships, and other international-level competitions from 2008 to 2017. Data were collected only from the finals or semifinals in each competition with a sampling rate of 60 Hz. To ensure homogeneity of data in all classes, we only included sprinters who satisfied the A-qualification standards of previous men's T42 (13.40 s). Each performance was the personal best time for a 100-m sprint for nearly each individual (Table 1). On average, relative differences between analyzed race times and personal best times were 100.74%, 100.61%, or 100.51% for sprinters with UTF amputation, BTF amputation, or FI without amputation, respectively. Individual athletes were excluded from the analysis if the athlete did not complete the race or if the athlete's body was not visible throughout the race. In our current dataset, sprinters with BTF amputation did not use prosthetic knee joints for either leg (i.e., no-knee conditions, in which a straight pylon attaches to the prosthetic socket and foot components). A similar approach of analyzing publicly available data from sports competitions for research purposes has been performed by Salo et al. (2011) for sprint running using 52 able-bodied sprinters; by Hobara et al. (2015) for prosthetic sprinting using 36 able-bodied, 25 unilateral amputee, and 17 bilateral amputee sprinters; and by Senefeld et al. (2016) for the finishing times of the top 10 men and women world record swimming performances (freestyle, backstroke, breaststroke, and butterfly) from 1986 to 2011 in swimmers between 25 and 89 years old.

Data analyses

Based on previous studies (Hobara et al. 2015, 2016), we determined the average speed (S_{100}) of each individual by dividing the race distance (100 m) with the official race times (t_{race}), which were obtained from each competition's official website. Thus,

$$S_{100} = 100/t_{race}. \quad (1)$$

In the present study, we calculated the average f_{step} as

$$f_{step} = N_{step}/t_{race}, \quad (2)$$

where N_{step} is the number of steps, which was manually counted by the authors. If we could not count the number of steps, we excluded the data from our analyses. The last step before the finish line was considered to be the last step. If an athlete's foot was on the finish line, we considered it as a step (Hobara et al. 2015). Since S_{100} is the product of f_{step} and average L_{step}, we calculated L_{step} by

$$L_{step} = S_{100}/f_{step}. \quad (3)$$

Table 1 Spatiotemporal parameters of athletes with unilateral transfemoral (UTF) amputations, bilateral transfemoral (BTF) amputations, and functional impairment (FI) without amputation during a 100-m sprint

Athletes	Group	Competitions and years	t_{race} (s)	S_{100} (m/s)	f_{step} (Hz)	L_{step} (m)	%PB
A1	UTF	IPC Athletics World Championships (final) 2015	12.13	8.24	4.45	1.85	100.00
A2	UTF	IPC European Championship (final) 2016	12.27	8.15	3.99	2.04	100.00
A3	UTF	IPC Athletics World Championships (semifinal) 2013	12.31	8.12	4.22	1.92	101.65
A4	UTF	Beijing Paralympic Games (final) 2008	12.32	8.12	4.38	1.85	101.99
A5	UTF	IPC Athletics World Championships (final) 2017	12.43	8.05	4.26	1.89	100.00
A6	UTF	International Wheelchair and Amputee Sports Athletics (final) 2011	12.47	7.99	4.55	1.75	101.71
A7	UTF	IPC Athletics World Championships (semifinal) 2015	12.61	7.93	4.20	1.89	100.00
A8	UTF	Parapan American Games (final) 2015	12.69	7.88	4.02	1.96	100.00
A9	UTF	IPC Athletics World Championships (semifinal) 2015	12.73	7.86	4.01	1.96	100.00
A10	UTF	Beijing Paralympic Games (final) 2008	13.08	7.65	4.13	1.85	102.83
A11	UTF	IPC Athletics World Championships (semifinal) 2015	13.29	7.52	3.99	1.89	100.00
A12	BTF	World Para Athletics Junior Championships (final) 2017	12.01	8.33	3.50	2.38	100.00
A13	BTF	IPC European Championship (final) 2016	12.21	8.19	4.10	2.00	100.66
A14	BTF	IPC Athletics World Championships (semifinal) 2015	12.82	7.80	3.98	1.96	101.77
A14	BTF	IPC European Championship (final) 2016	13.07	7.54	3.39	2.22	100.00
A16	FI	IPC Athletics World Championships (final) 2015	12.24	8.17	4.17	1.96	100.00
A17	FI	IPC Athletics Asia-Oceania Championship (final) 2016	12.62	7.92	4.36	1.82	100.00
A18	FI	IPC European Championship (final) 2016	12.70	7.87	4.09	1.92	100.87
A19	FI	London Paralympic Games (final) 2012	12.73	7.86	4.24	1.85	101.68
A20	FI	Rio Paralympic Games (semifinal) 2016	12.76	7.84	4.15	1.89	100.00

%PB indicates the relative differences between analyzed race time and personal best time in each individual

We also calculated the Lf_{ratio} as

$$Lf_{ratio} = L_{step}/f_{step}. \quad (4)$$

Statistical analysis

Before the statistical analyses, Levene's test was performed to test for equal variance across groups or samples. Since none of the data were homogeneous or normally distributed, the Kruskal–Wallis test was used to compare spatiotemporal parameters among the three groups. We also calculated the effect size (ES) for the Kruskal–Wallis test using Cramer's *V*. From this ES calculation, the results were interpreted as small (0.1–0.3), medium (0.3–0.5), or large (> 0.5), as described by Cohen (1988). If a significant main effect was observed, the Mann–Whitney *U* test was repeated for all combinations in each variables as a post hoc multiple comparison. We also determined whether the Lf_{ratio} for all individuals was within the 1.96 standard deviation (SD). These statistical analyses were executed using SPSS version 19 (IBM, Chicago, IL, USA).

Results

Figure 1 shows the relationship between f_{step} and L_{step} for all individuals in the three groups. Dotted lines indicate the finish times determined using the combination of f_{step} and L_{step}. As shown in Fig. 2a, there was no significant main effect of groups on S_{100} ($\chi^2_{(2)} = 0.28$, $p = 0.87$, ES = 0.08). We found a significant main effect of groups on the f_{step} (Fig. 2b; $\chi^2_{(2)} = 6.54$, $p < 0.05$, ES = 0.41). Although f_{step} in athletes with BTF amputation was significantly lower than in athletes with UTF amputation or FI without amputation ($p < 0.05$), there was no significant difference in f_{step} between athletes with UTF amputation and those with FI without amputation. Statistical analysis also revealed that there was a significant main effect of groups on L_{step} (Fig. 2c; $\chi^2_{(2)} = 7.48$, $p < 0.05$, ES = 0.43), where the L_{step} in athletes with BTF amputation was significantly longer than in athletes with UTF amputation or with FI without amputation ($p < 0.05$). However, there was no significant difference in L_{step} between athletes with UTF amputation and FI.

As shown in Fig. 3a, a significant main effect of groups on the Lf_{ratio} ($\chi^2_{(2)} = 7.61$, $p < 0.05$, ES = 0.44) was found. Although the Lf_{ratio} in athletes with BTF amputation was significantly greater than in athletes with UTF amputation or with FI without amputation ($p < 0.05$), there was no significant difference in the Lf_{ratio} between athletes with UTF amputation and those with FI without amputation. As shown in Fig. 3b, all athletes, except for two with BTF amputations (A13 and A14), exhibited an Lf_{ratio} within the 1.96 SD.

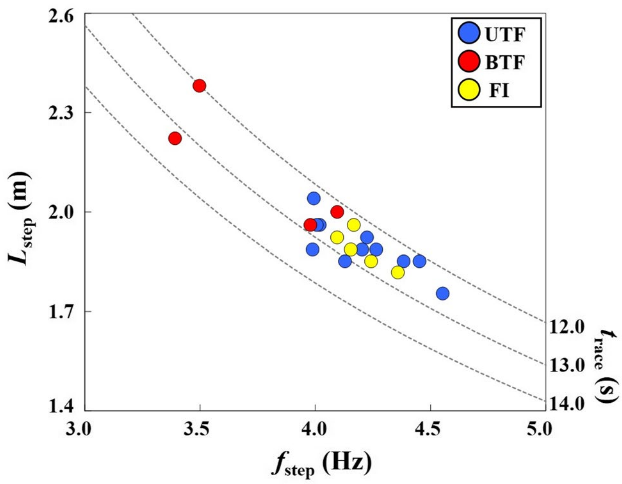

Fig. 1 Relationships between average step frequency (f_{step}) and step length (L_{step}) across the three groups. Unfilled, gray, and black circles indicate data for sprinters with unilateral transfemoral (UTF) amputations, bilateral transfemoral (BTF) amputations, and functional impairment (FI) without amputation, respectively. Dotted lines denote the official race times

Discussion

The aim of this study was to investigate the spatiotemporal parameters in sprinters with UTF amputation, BTF amputation, or FI without amputation during a 100-m sprint. There was no significant difference in S_{100} among the three groups, but athletes with BTF amputation were characterized by significantly lower f_{step} and longer L_{step} than athletes with UTF amputation or with FI without amputation (Fig. 2a–c). Furthermore, as shown in Fig. 3a, b, the Lf_{ratio} of athletes with BTF amputation was greater than in the other two groups. These results support our hypothesis that athletes with BTF amputation exhibit lower f_{step} but longer L_{step} than athletes with UTF or with FI without amputation during 100-m sprint. To our knowledge, this is the first study describing running mechanics in athletes with BTF, UTF and FI.

A recent study investigated the differences in spatiotemporal parameters between BTF and UTF amputees (non-athletes) when walking on level ground at a self-selected speed (Javis et al. 2017). The authors found that BTF amputees exhibited slower walking speed with slightly lower cadence and shorter step length than those with UTF amputation during walking. In contrast, the present data indicate that athletes with BTF amputation had a lower f_{step} but longer L_{step} than athletes with UTF amputation (Fig. 2b, c). In our current dataset, sprinters with BTF amputation did not use prosthetic knee joints for either leg (i.e., no-knee conditions). Further, all sprinters with BTF amputation used carbon-fiber prosthetic feet (running-specific prosthesis), which have high energy return with less hysteresis than intact human feet (Brüggemann et al. 2009; Beck et al. 2016). Generally, these running-specific prosthetic components are not for daily use, such as walking. In addition, the activity level of participants in the current study is also different from those of the previous study (Javis et al. 2017), in which one of the

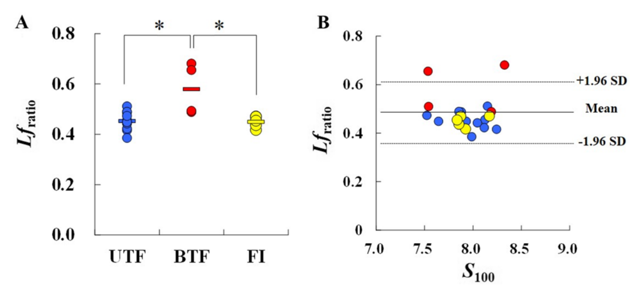

Fig. 3 **a** Comparisons of the step length/step frequency ratio (Lf_{ratio}) across the three groups. Asterisk: significant differences between the two relevant groups at $p<0.05$. **b** Lf_{ratio} as a function of average speed (S_{100}). White, gray, and black circles and bars indicate individual data and average values for athletes with unilateral transfemoral (UTF) amputations, bilateral transfemoral (BTF) amputations, and functional impairment (FI) without amputation, respectively

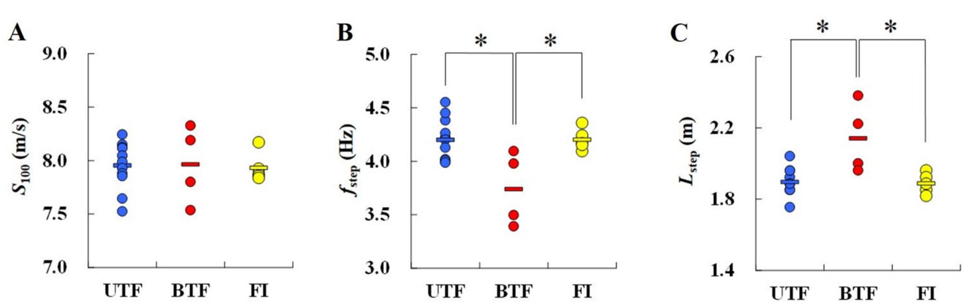

Fig. 2 Comparisons of average speed (S_{100}) (**a**), step frequency (f_{step}) (**b**), and step length (L_{step}) (**c**) across the three groups. White, gray, and black circles and bars indicate individual data and average values for athletes with unilateral transfemoral (UTF) amputations, bilateral transfemoral (BTF) amputations, and functional impairment (FI) without amputation, respectively. Asterisk: significant differences between the two relevant groups at $p<0.05$

inclusion criteria was "they could walk continuously for at least 12 min". Meanwhile, all sprinters in the present study satisfied the A-qualification standards of previous men's T42 (13.40 s in the 100-m sprint). Therefore, differences in step characteristics during walking and running between those with UTF and BTF amputation may be varied by prosthetic knee and foot components, subject's activity levels, or any combination of these variables.

We found significant differences in f_{step} across the three groups, where the f_{step} in sprinters with BTF amputation was significantly lower than in sprinters with UTF amputation or with FI without amputation (Fig. 2b). Current results agree with a past finding that athletes with BTF amputation exhibited lower f_{step} than athletes with UTF during 200-m sprint (Hobara et al. 2018). A possible explanation for the lower f_{step} in sprinters with BTF amputation may be the compensatory mechanism for insufficient knee flexion during the swing phase through circumduction at the hip. According to previous studies, knee flexion in persons with transfemoral and knee disarticulation amputation was insufficient for safe obstacle crossing during gait, which resulted in a circumduction strategy by hip abduction (Vrieling et al. 2007, 2009). These kinematic adaptations would be more apparent in sprinters with BTF amputation because they require the use of transfemoral prostheses in both legs. Moreover, in the present study, sprinters with BTF amputation did not use prosthetic knee joints for either leg. Therefore, the lack of knee strategy in sprinters with BTF amputation was compensated by circumduction at the hip on the prosthetic side, thereby resulting in a reduced f_{step} through longer swing time during sprinting than the other two groups.

As shown in Fig. 2c, the L_{step} in athletes with BTF amputation was significantly longer than in athletes with UTF amputation or with FI without amputation. Current results partly agree with a recent finding that demonstrated that athletes with BTF was characterized by longer L_{step} than athletes with UTF during 200-m sprint (Hobara et al. 2018). A previous study (Hunter et al. 2004) suggested that the L_{step} during sprint running is partly explained by the segment positions at touchdown and take-off, segment inertial parameters, horizontal velocity at touchdown, relative horizontal and vertical GRF impulse, and air resistance during the stance phase. A previous study also revealed that sprinters with UTF amputations who are wearing running-specific prosthesis during sprinting had smaller braking GRF impulses in their prosthetic leg than in their intact leg at around the 20-m mark (Makimoto et al. 2017). Notably, they also demonstrated that there were no significant differences in propulsive GRF impulses between prosthetic and intact legs (Makimoto et al. 2017). Therefore, although we did not measure the continuous changes of spatiotemporal parameters, it is reasonable to assume that sprinters with BTF amputations may be able to increase their L_{step} to a greater extent than can sprinters with UTF amputations or with FI without amputation through smaller braking GRF at the expense of vertical GRF.

As shown in Fig. 3a, the Lf_{ratio} of sprinters with BTF amputations was significantly greater than in the other two groups, but there was no significant difference in the Lf_{ratio} between athletes with UTF amputation and those with FI without amputation. These results indicate that the spatiotemporal coordination of sprinting is not the same between sprinters with BTF amputations and sprinters with UTF amputations or with FI without amputation. Furthermore, we also found that the Lf_{ratio} in 18 individuals in the current dataset were within the 1.96 SD, whereas two sprinters with BTF amputations were not (Fig. 3b). In other words, despite the relatively greater number of sprinters with UTF amputations ($n = 11$) or FI without amputation ($n = 5$) than sprinters with BTF amputations ($n = 4$), all sprinters with UTF amputations or FI without amputation showed similar spatiotemporal coordination of sprinting. However, even in a small sample size, 50% of sprinters with BTF amputations in the current dataset demonstrated a clear deviation from reference intervals of spatiotemporal coordination. Therefore, the current results suggest that contrary to sprinters with UTF amputations or FI without amputation, the spatiotemporal patterns of sprinters with BTF amputations could deviate from reference intervals of spatiotemporal patterns during sprinting with a certain probability.

There are certain considerations that must be acknowledged when interpreting the results of the current study. First, due to the limited number of subjects who can perform sprinting with A-qualification standard, only 20 sprinters with BTF, UTF, and FI were available for analysis in the present study. Notably, sprinters with BTF amputation ($n = 4$) may not be homogeneous within the group, because two of the four athletes in this group showed clear differences from the other two in several spatiotemporal parameters during sprinting (Figs. 1, 2, 3). In other words, at least 50% of the sprinters with BTF amputations may have similar spatiotemporal patterns to sprinters with UTF amputation or with FI without amputation. Additionally, since the statistical power to assess group difference may be insufficient, caution needs to be taken regarding the interpretation and generalization of these findings. Second, we could not control the subjects' demographic data, such as age, body height, and weight among the three groups. Although a previous study suggested that there were no significant relationships between body height and spatiotemporal parameters in sprinters with UTF amputation (Hobara et al. 2017), it is still unclear whether demographic data affected the spatiotemporal parameters during sprinting in the current data set. Since the observed differences in spatiotemporal parameters among the three groups may be attributed not only to types of disability but also their demographic data, care should be taken to control for these parameters in the future study. Finally, we calculated the L_{step} using the number of steps taken and the race time. However, not all the steps would be of the same length. For example, many short steps may be taken in the initial acceleration phase from the start. Indeed, Salo et al. (2011) subtracted a distance of 0.55 m and a time of 0.52 s from the calculations of averaged L_{step} and f_{step} based on their pilot test. This is because the first step out from the starting blocks does not cover as much ground as all subsequent steps and it clearly takes the longest time. Therefore, the present data should be interpreted as "averaged" f_{step} and L_{step} across the 100-m distance.

Conclusion

In this study, we investigated the differences in the spatiotemporal parameters among sprinters with UTF amputations, BTF amputation, and FI without amputation during the 100-m sprint in official competitions. Although there were no significant differences in the average speed across the three groups, sprinters with BTF amputation showed a significantly lower f_{step} and longer L_{step} than the other two groups. Our data support recent revisions of classification rules (January 1, 2018), where sprinters with UTF amputations and FI without amputation are competing together in the same 100-m sprint race, and sprinters with BTF amputation are excluded at several competitions.

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Author contributions The study was designed by HH, SH, WP, and RM; HH, SH, YK, and JF wrote the paper with substantial contribution from YN, RM, and WP data were collected by HH. Analyses were performed by HH and SH

Compliance with ethical standards

Conflict of interest None of the authors have any conflicts of interest associated with this study.

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