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Influence of weighted cuffs on ground reaction forces in running of an elite unilateral upper extremity amputee athlete

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Abstract

Due to their opposing movement the swinging arms are considered not to have a major contribution to the overall motion of running. However, missing one upper extremity limb can lead to significant asymmetries. In the present study it was investigated what influence weighted cuffs, which are added to the missing limb, have on the ground reaction forces in running of an elite unilateral upper extremity amputee athlete. One elite athlete (PB 400m: 0:48.45, PB 800m:1:50.92) currently classified as T47 by the International Paralympic Committee due to missing his right forearm participated in this study. The subject had to perform several runs on a 100m Tartan track with a velocity of 8 m/s (high race speed) without and with wearing two differently weighted cuffs (0.5 kg and 1 kg) applied to the elbow of the impaired limb. Ground reaction forces (GRFs) were captured using four floor-level mounted Kistler force plates, mean vertical and horizontal GRFs were calculated over 100% of stance phase duration and statistical data was evaluated for maximum and minimum values. Patterns of vertical GRFs did not differ dramatically whereas the maximum vertical force revealed a highly significant and significant difference between left and right foot when running with heavy or no additional weight respectively. Overall results showed only singular differences for different weight conditions, but several statistically significant differences between left and right foot were found independent from weight conditions.

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1. Introduction

The function of the upper extremities during human locomotion has been of minor interest so far. In the late 1980ies two studies were published [1,2] investigating the arms contribution to running and found a small, but potentially important contribution with increasing importance with increasing running speed. Similar findings were observed by Lees and Barton[3] using a different calculation algorithm.

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Other than that, quite a number of studies exists that have been published with focus on the effect of arm swing restrictions on the human gait and during slow running, such as different changes in ground reaction forces (GRFs) [4–7].

According to Novacheck[8] kinetics most importantly the GRFs is one of three major fields of interest in walking and running biomechanics, besides kinematics and electromyography. To allow an intersubjective comparison GRFs are usually normalized to parameters such as body weight (BW), body weight times height (BWH) or body weight times leg length (BWL) [9].

Several studies have been carried out at different running and walking speeds, conclusively leading to a significant relationship between running speed and GRFs with the result that higher running speeds lead to higher peak forces and shorter force periods [10–13]. At a running speed of 4.5m/s Cavanagh and Lafortune[14] measured GRFs of 3 times BW in the vertical, 1 times BW in the anterior-posterior and 0.3 times BW in the medial-lateral direction with considerable differences between the subjects (N=17). Further Munro et al.[11] reported to have found physiological right-left asymmetries within individuals.

Based on the findings by Hinrichs[15] in 2010 the International Paralympic Committee (IPC) found impairments of the upper extremities between the wrist and the elbow (i.e. loss of a forearm) to lead to negligible limitations in middle- and long-distance running. Since after the Paralympic Games in London 2012 athletes affected by this have only been allowed to start in events up to 400m, which are started from a crouch position where a clear disadvantage is still given [16]. As long as the principles: safety, fairness, universality and physical prowess apply, it is allowed by IPC to use technology and equipment, such as sports specific prosthetic devices [17].

However, the lack of research in this area and the decisions presented by the IPC lead to the following research question (Q) and hypothesis (H):

Q: What influence does the use of weight cuffs additionally added to the impaired limb have on the horizontal and vertical GRFs of an elite unilateral upper extremity amputee athlete?

H: Weight added to the impaired limb can partly compensate the missing mass and therefore affects any asymmetries observable when running without additional weight cuff.

2. Methods and materials

One high-caliber male middle-distance runner (age: 26 years, height: 183 cm, weight: 67 kg, PB 400m [min:s]: 0:48.45, v_{mean} 400m: 8.3 m/s, PB 800m [min:s]: 1:50.92, v_{mean} 800m: 7.2 m/s) currently classified as T47 by the IPC due to unilateral dysmelia (aplasia) of right forearm (including the hand) took part in the study. The subject was informed about the intended procedure and gave his oral consent prior to the measurements.

In order to create highly realistic conditions, four Kistler force plates (0.6m times 0.9m, 8 channel amplifier type 9865, Kistler Instrumente AG, Winterthur, SUI) were mounted on floor level and aligned consecutively along a 100m indoor Tartan track at the German Sports University Cologne. The subject was asked to perform several (at least four valid) runs on this track with a high running speed of approximately 8 ± 0.5 m/s based on his personal bests, while the force plates were sampling data at a rate of 1000Hz. The running speed was controlled via two double light barriers placed 0.5m before and 0.55m after the force plate section and resulted in an actual speed of 8.09 ± 0.17 m/s.

A trial was considered valid if at least one foot made ground contact fully on one of the four force plates without overstepping (Figure 1(a),(b)) and running speed was within the predefined range.

Three running conditions no, light and heavy were defined in regard to the weight added to the impaired limb using either no weight cuff or cuffs with 0.5kg or 1kg, respectively, on the right upper arm, proximal of the elbow (Figure 1(c),(d)).

Data processing was done with Matlab 7.04 (The Mathworks, Natick, USA). Horizontal (anterior-posterior (F_x) and medial-lateral (F_y)) and vertical ground reaction forces (F_z) of the stance phases for left and right foot were interpolated to 100% of the stance phase by detecting initial contact (IC) and toe-off (TO) on the force plate. Data were filtered with a zero-lag digital forward reverse moving average filter using a window width of 12ms and any offset value (mean value of 20 samples of the unloaded force plate) was subtracted from each channel. Additionally all values within a defined range of $-8N < x < +8N$ were set to zero to allow a clear discrimination between loaded and unloaded state. IC was then defined as the instance in time where the vertical GRF (F_z) exceeded the threshold used for the offset correction. TO on the other hand was calculated by finding the first instance in time after IC where

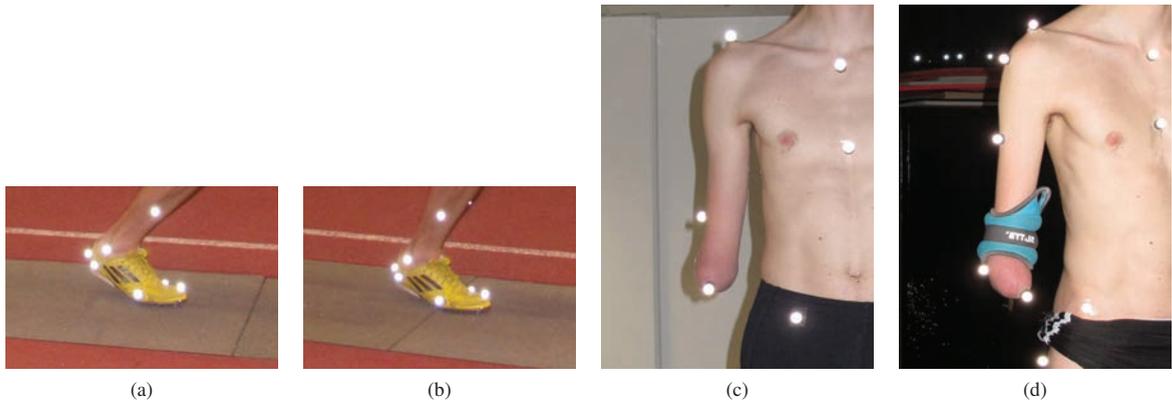


Fig. 1. Subject with markers attached and (c) no weight cuff, (d) weight cuff on the right upper arm proximal of the elbow. Ground contact on the force plates (a) valid ground contact, i.e. full contact area on one force plate, (b) invalid ground contact, i.e. ground contact on two force plates (overstepping).

the vertical GRF (F_z) was below threshold again.

Furthermore they were normalized to the subject’s BW and statistical values for the maximum (and minimum where applicable) GRFs were obtained applying a paired student-t-test ($\alpha = 5\%$, $p < 0.01$ highly significant, $p < 0.05$ significant).

3. Results

Figure 2(a), (b) and (c) show the anterior-posterior GRF (F_x), which clearly reveals the typical braking and acceleration force pattern in all three conditions. Left and right foot do not show any clear differences, neither do the different conditions, which is further supported by the values in Table 1. Minima and maxima as well are nearly identical, and no statistically significant differences could be found neither between the different weight conditions, nor between left and right foot.

For the medial-lateral GRF (F_y), shown in Figure 2(d), (e) and (f), no significant differences were observed for the different load conditions, but highly significant differences ($6.6 \cdot 10^{-6} \leq p \leq 0.0133$) could be found for left-right differences in each weight condition - except for the minimum F_y in light weight condition ($p = 0.60$) - for maximum (at approx. 10% of SP) and minimum (at approx. 27% of SP).

Table 1. GRF data (F_x, F_y, F_z in times BW) for three conditions (no, light and heavy weight) for the left (l) and right (r) foot 8m/s. max, min: mean maximum, minimum \pm SD, max@%SP, min@%SP: occurrence of the maximum and minimum in % of SP. sig: level of significance for left-right differences: **: highly significant ($p < 0.01$), *: significant ($0.01 < p < 0.05$).

		no weight			light weight			heavy weight		
		l	sig	r	l	sig	r	l	sig	r
F _x	min	-0.71±0.01		-0.72±0.02	-0.72±0.01		-0.71±0.02	-0.71±0.01		-0.72±0.03
	min@%SP	72		72	72		72	72		72
	max	0.95±0.07		0.99±0.06	0.96±0.11		0.96±0.05	1.00±0.06		1.00±0.04
	max@%SP	10		11	10		10	10		11
F _y	min	-0.43±0.06	*	-0.40±0.06	-0.35±0.08		-0.32±0.04	-0.39±0.04	**	-0.40±0.04
	min@%SP	27		28	27		27	27		27
	max	0.17±0.02	**	0.28±0.06	0.20±0.03	**	0.41±0.08	0.22±0.05	**	0.28±0.05
	max@%SP	11		10	11		10	11		11
F _z	max	3.97±0.19	*	3.52±0.19	3.88±0.21		3.42±0.16	3.84±0.15	**	3.38±0.16
	max@%SP	22		23	21		21	20		23

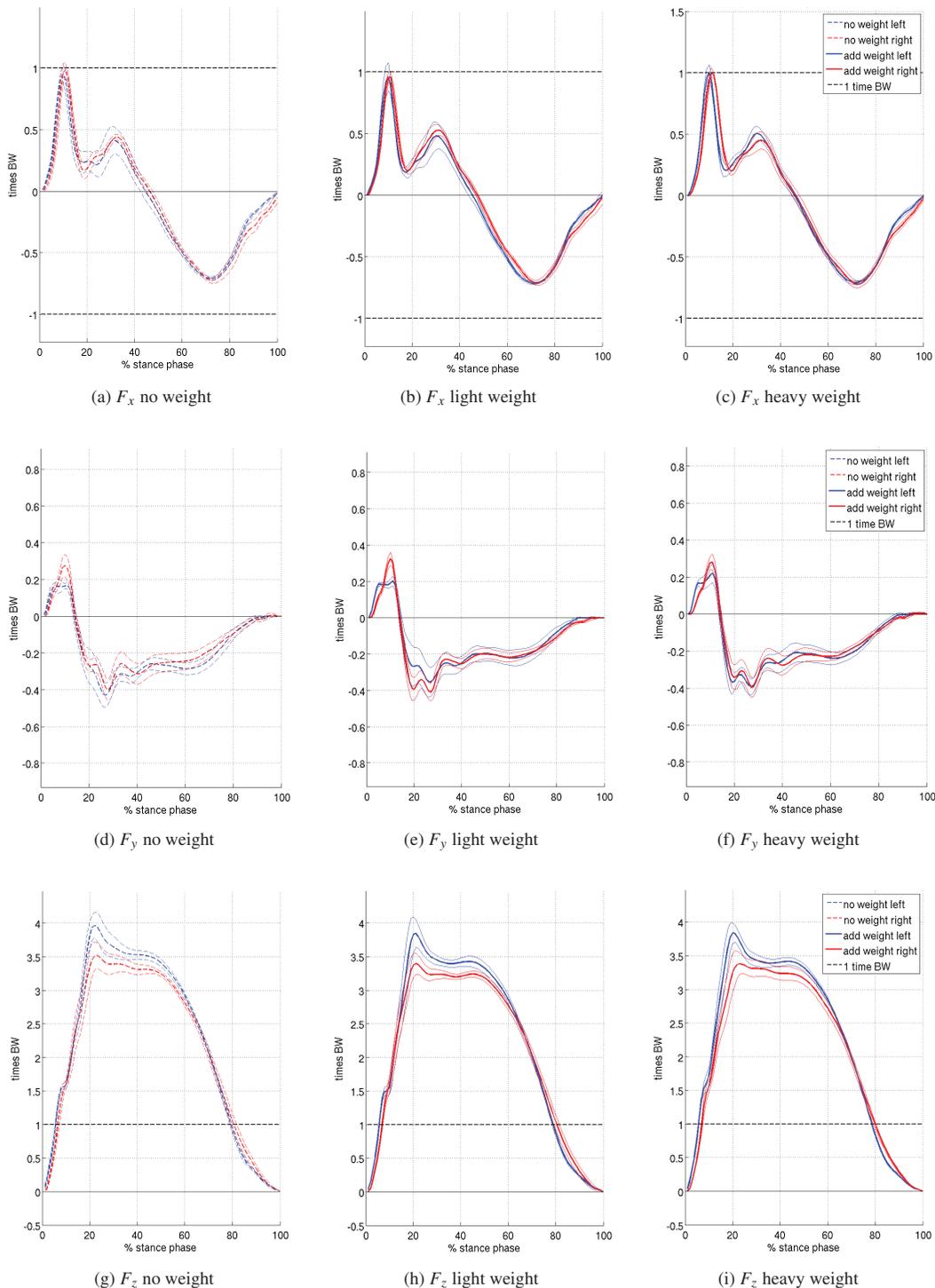


Fig. 2. GRFs at a running speed of 8m/s. (a), (b), (c) antero-posterior GRFs (F_x , positive: braking force, negative: acceleration force); (d), (e), (f) medio-lateral GRFs (F_y) and (g), (h), (i) vertical GRFs (F_z) without, with light and heavy additional weight attached to the impaired limb plotted over 100% of the stance phase in times BW, blue: left, red: right, thick lines: mean, thin lines: \pm standard deviation.

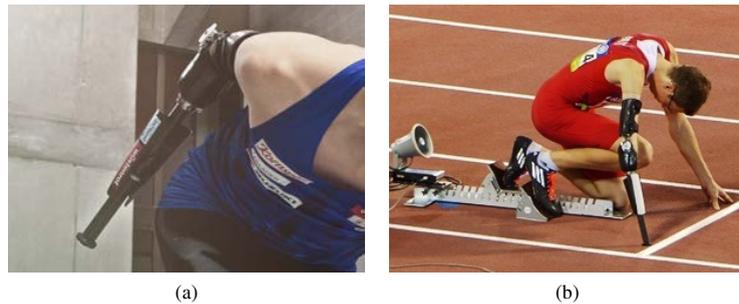


Fig. 3. New forearm prostheses used by the athlete (a) close up; (b) Prostheses enables athlete an improved crouch start position (sources: (a)https://www.wuestenrot.at/content/dam/contentbilder/sponsoring/Guenther_Matzinger_Print_4.jpg, (b)http://parasport.at/fileadmin/Bilder/News/2015/151022_leichtathletik_matzinger_wm_doha_2_internet.jpg)

Although all three weight conditions show clear left-right asymmetries for the vertical GRF (F_z) (Figure 2(g), (h) and (i)) it seems, as if this difference over the whole pattern decreases with increasing additional weight. However, the left-right differences for maximum F_z remain constant (at approx. 0.45 times BW less F_z for the right foot, cf. Table 1) and for no weight and heavy weight these differences were significant ($p = 0.023$) and highly significant ($p = 0.0026$), respectively. No significant left-right difference was found for the light weight condition ($p = 0.066$). Statistical evaluation of the different weight conditions again yielded no statistically relevant results.

4. Discussion and conclusion

In terms of anterior-posterior GRF no significant asymmetries at all could be identified in the case of the present athlete with unilateral upper limb impairment. This leads to the assumption, that this type of impairment does not affect the small part of acceleration and deceleration, which is described by this force. Further with not even half the BW also the medial-lateral GRF, although revealing highly significant left-right differences in all three conditions in terms of maximum value, is not thought to have a major influence on the overall movement. When running with light additional weight no significant asymmetry in terms of minimum F_y (i.e. lateral component of the GRF) could be observed. However, a highly significant difference that could be reported with heavy weight and no significant difference between the weight conditions in any value lead to the assumption that additional weight does not affect the medial-lateral GRF in this case.

The vertical GRF, which reaches maximum values of up to nearly four times BW, did reveal significant and highly significant asymmetries (left-right differences) for the conditions without and with heavy additional weight. Although the difference is similarly visible in the GRF pattern with the light weight cuff, it did not lead to any significance. Hence, it would seem premature to draw the conclusion that a light weight cuff would even out the asymmetry. If that were the case it could also lead to the assumption that heavy weight would lead to an exact opposite difference between left and right, which could further not be observed in the data.

Summed up the hypothesis presented earlier has to be rejected as on the one hand for F_x no asymmetries could be found at all and on the other hand the asymmetries found within F_y and F_z could not be clearly reduced or evened out. However, this study raised several limitations and problems. First and foremost it is a single case study only, as similar subjects (with similar impairment and similar skills) were not available and unfortunately will also hardly be available in the future mainly due to geographic distances.

Secondly, the number of trials the subject could perform within the given time and, although offering individual resting periods, without major fatigue, which could have a further influence the results was very limited.

Thirdly, the use of simple weight cuffs in order to make up for the missing limbs other than a special prosthesis is doubtful. However, a prosthesis, which would more realistically mimic the mass moment of inertia of the missing limb, was not available at the time of measurements and the weight cuffs were the athletes preferred equipment in practice for this matter at the time. It can further be mentioned that based on the limitations of the results presented here in combination with the personal interest of the athlete such a prosthesis has yet been produced and is now

regularly used by the athlete in competition as well as practice (Figure 3a). A follow-up study, unfortunately, could not yet be realized.

Last, due to the type of impairment and hence not having been able to use his hands for his whole life (for training and activities of daily living) the subject shows overall malposition of the upper body (elevated left shoulder, uneven pelvis, scoliosis, etc.), which might just not be evened out by simply adding weight. Also adding weight via a cuff as used here does not provide a lever arm, which is usually given by the forearm. This is one reason why the subject nowadays has chosen to run with a special prosthesis, which is also allowed during competitions and further enables him a better crouch start position (Figure 3b).

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