



Adjustments after an ankle dorsiflexion perturbation during human running

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ABSTRACT

In this study we investigated the effect of a mechanical perturbation of unexpected timing during human running. With the use of a powered exoskeleton, we evoked a dorsiflexion of the right ankle during its swing phase while subjects ran on a treadmill. The perturbation resulted in an increase of the right ankle dorsiflexion of at least 5°. The first two as well as the next five steps after the perturbation were analyzed to observe the possible immediate and late biomechanical adjustments. In all cases subjects continued to run after the perturbation. The immediate adjustments were the greatest and the most frequent when the delay between the right ankle perturbation and the subsequent right foot touch-down was the shortest. For example, the vertical impact peak force was strongly modified on the first step after the perturbations and this adjustment was correlated to a right ankle angle still clearly modified at touch-down. Some late adjustments were observed in the subsequent steps predominantly occurring during left steps. Subjects maintained the step length and the step period as constant as possible by adjusting other step parameters in order to avoid stumbling and continue running at the speed imposed by the treadmill. To our knowledge, our experiments are the first to investigate perturbations of unexpected timing during human running. The results show that humans have a time-dependent, adapted strategy to maintain their running pattern.

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1. Introduction

Running is one of the most popular recreational activities. This could explain why the biomechanics of normal running are so well documented [1,2]. Although in the real world humans must negotiate various perturbations during running, little is known about the way they do it.

In walking, the effects of unexpected perturbations such as slipping [3], tripping [4], obstacle avoidance [5,6], loss of ground support [7] or unexpected compliant surface [8] have been investigated. For any given perturbation, rapid and appropriate adjustments have been observed allowing the subjects to avoid falling and continue walking. Perturbations such as a mechanically evoked ankle dorsiflexion have also received a lot of interest during walking [9,10]. The amplitude of the plantar-flexor muscles reflex responses was investigated but little attention was paid to the walking pattern adjustments realized by the subject after that perturbation.

In running, Grimmer and colleagues [11,12] measured the biomechanical adjustments made by subjects running over an uneven track which incorporated a clearly visible force plate of adjustable height. The runners maintained their running pattern

by adjusting their leg contact angle and ankle joint stiffness to the height of the vertical step.

In animals, the strategies used to negotiate an unexpected perturbation during running have been discussed over the last 10 years [13–16]. Jindrich and Full [13] showed that a running cockroach pushed to one side, recovered within two strides and continued running on its original path. Daley and colleagues [14–16] investigated the reactions of guinea fowl to an unexpected drop in terrain height during running. The drop of 8.5 cm (approximately 40% of the leg length) was dissimulated by a thin paper. In all experimental trials, the guinea fowls recovered and continued running at about the same preferred speed as before; in only one trial, an animal stumbled, but without falling.

Daley [17] and Alexander [18] consider that dynamic stability is the ability of a system to continue a pattern of motion in the face of small disturbances. This ability has been observed after an unexpected perturbation in human walking [3–8] and animal locomotion [13–16]. To our knowledge, no study has investigated unexpected perturbation during human running.

In this study, we investigated the adjustments made to the running pattern after an ankle perturbation of unexpected timing, by measuring the angular position of the ankle and the ground reaction forces. We used an innovative powered ankle-foot exoskeleton to mechanically evoke ankle dorsiflexion at random timing inside the swing phase. We observed whether the adjustments were modulated as a function of the perturbation

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timing. The two steps following the perturbation were analyzed for the immediate adjustments made by the subject, and the subsequent five steps were analyzed for the late adjustments.

2. Methods

2.1. Subjects

Seven healthy young men (age = 26.2 ± 2.2 years, body mass = 75.6 ± 9.1 kg, height = 1.81 ± 0.03 m) participated in this study. All subjects were free of lower leg injuries at the time of the experiment. Subjects were informed of the experimental conditions and provided their written consent to participate. Experiments were performed according to the Declaration of Helsinki and approved by the local ethics committee.

2.2. Materials

All subjects ran on an instrumented treadmill at a speed of 2.8 m s^{-1} while wearing regular running shoes and equipped with a powered exoskeleton on their right leg (Fig. 1A and B).

This new device, inspired by that of Andersen and Sinkjær [19], was designed to deliver a well-defined perturbation to the right ankle joint while the subject is running on the treadmill. It consists of two carbon fiber shells, custom-made for each subject, placed around the foot and the lower leg. The shells are linked by a joint pivoting at the center of rotation of the ankle and allowing only dorsi-plantar movements. An optical encoder in the pivot (1 kHz sampling rate, Avago Technologies[®], HEDS-9200) measured the angular position of the ankle ($^{\circ}$). A clutch and actuator (SEW[®]), connected to a servomotor (Parker Compumotor[®] AT6250) by Bowden cables, could flex the ankle at speeds up to $600^{\circ} \text{ s}^{-1}$ with a

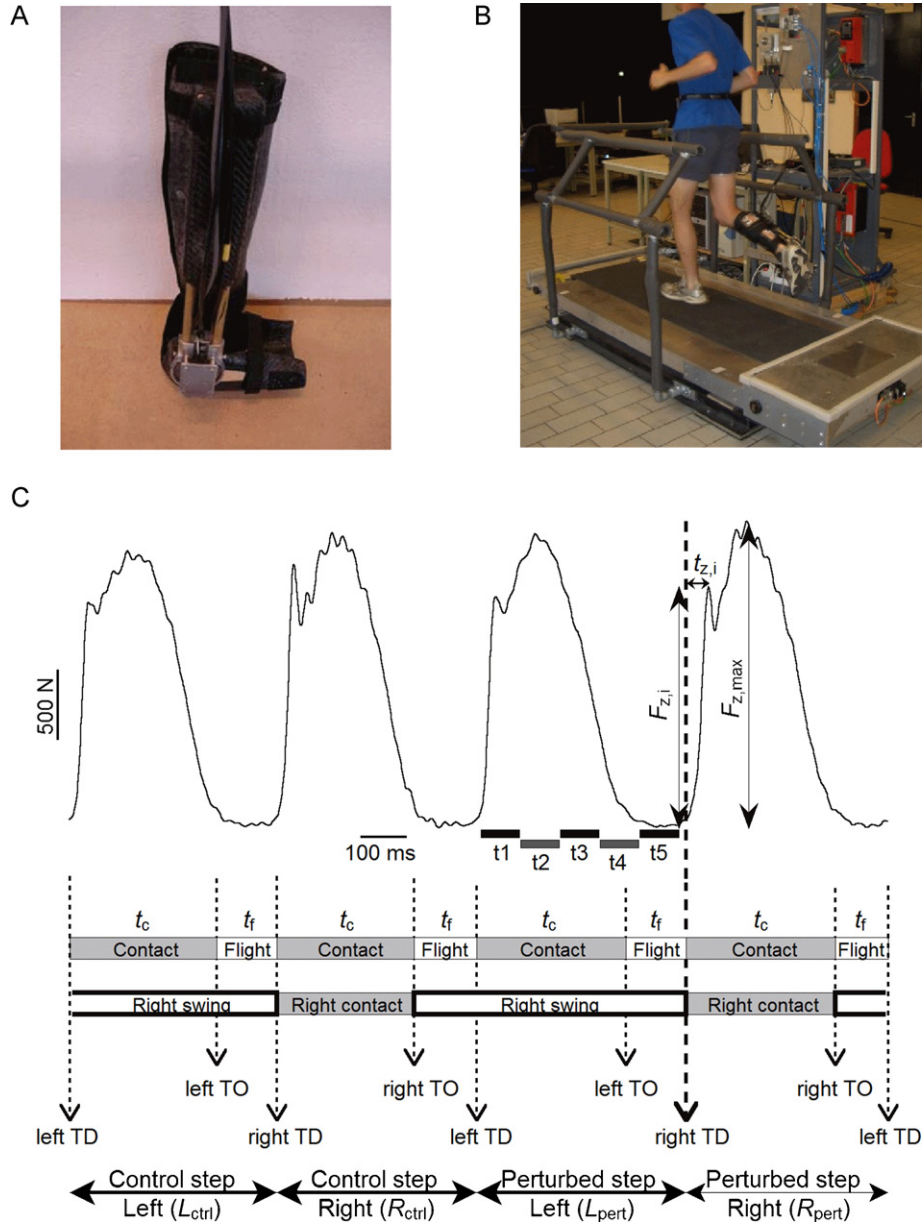


Fig. 1. (A) Powered exoskeleton designed to deliver a perturbation to the right ankle joint during running. Two carbon fiber shells around the foot and the lower leg are linked by a hinged joint pivoting at the center of rotation of the ankle. (B) Subject with exoskeleton running on the treadmill. (C) Typical trace of the vertical ground reaction force (F_z , N) of one subject; only the first four steps of the sequence, including the control steps (L_{ctrl} and R_{ctrl}) and the perturbed steps (L_{pert} and R_{pert}), are shown. TD = touch-down of a foot. TO = toe-off of a foot. L or R for left or right, ctrl or pert subscripts for control or perturbed steps. The vertical interrupted line indicates the first TD following the perturbation (right TD). The vertical dotted lines indicate TD or TO. The white boxes represent the swing phases while the grey boxes represent the contact phases. Perturbations were applied to the right ankle during its swing phase, more precisely during the contact phase of the left foot or the flight phase preceding the right TD, i.e. during L_{pert} as defined at the bottom of Fig. 1C. The perturbations were classified into five timing groups as shown: t1, t2, t3, t4 and t5, see Section 2 for details. The parameters t_c , t_f , $F_{z,max}$, $F_{z,i}$ and $t_{z,i}$ are described in the text.

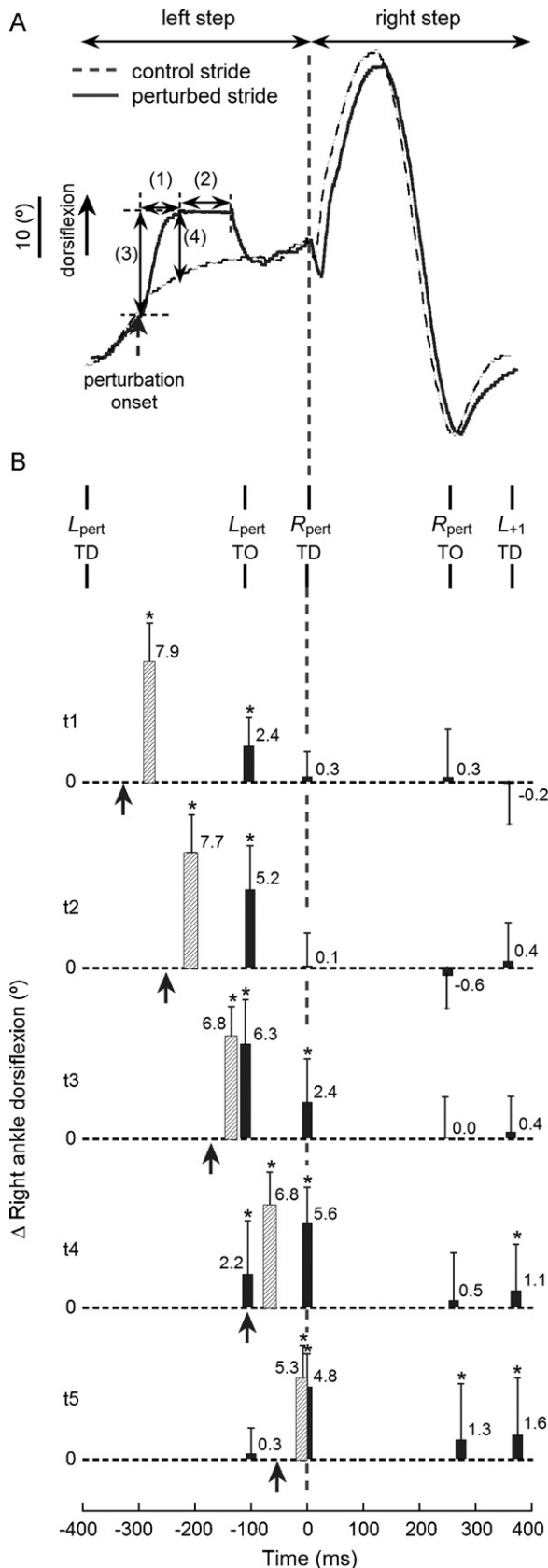


Fig. 2. Effect of the perturbation on the right ankle angle. Panel A shows an example of the right ankle dorsiflexion for a t2 timing group perturbation. The control stride (dashed trace) and the perturbed stride (continuous trace) are superimposed and synchronized on the right TD (time 0, vertical interrupted line). The dashed arrow shows the perturbation onset. The rise time (1) is the duration from the beginning of the perturbation to a plateau. The hold time (2) corresponds to the duration during

maximal torque of 300 N m. The clutch and actuator could be activated at any predetermined moment during running. The whole device weighs less than 1 kg. As a part of the device was worn inside the right shoe, an insole was placed in the left shoe to compensate for the thickness of the right foot shell.

A strain-gauge sensor under each corner of the treadmill (1 kHz sampling) measured the three orthogonal components of the ground reaction force (GRF) [20]: vertical F_z , fore-aft F_y and lateral F_x , in N.

2.3. Experimental protocol

Each session started with the habituation of the subject to the treadmill. Two 1-min runs were first recorded, then the subject was equipped with the exoskeleton and after habituation we again recorded two 1-min runs without perturbation. Thereafter perturbations consisting of dorsiflexion of the right ankle were evoked at any time during running.

The perturbations analyzed in this paper were provoked during the swing phase preceding the right foot touch-down (right TD, Fig. 1C). The timing of the perturbation was predetermined using a delay relative to the left foot touch-down (left TD), determined from the F_z . The same perturbation timing was used for 3–7 successive perturbations, and then randomly modified. There were randomly 15–30 steps between two successive perturbations, to avoid subject anticipation and cumulative effects of the perturbations. The number of perturbations analyzed by subject was variable (from 27 to 122).

2.4. Data processing

The angular position of the right ankle and the GRFs were recorded on a personal computer and analyzed with Labview[®] v8.6.

A 10-steps sequence beginning with a left TD was used to analyze the effect of the perturbation (Fig. 1C). We defined a step as the period between one TD and the next one. The right ankle was always perturbed during a swing phase, specifically during a left step (L_{pert}). The seven steps following L_{pert} (R_{pert} , L_{+1} , R_{+1} , ...) were used to analyze the perturbation effects. The two preceding steps were used as control (L_{ctrl} , R_{ctrl}); L_{ctrl} was the reference for L_{pert} , L_{+1} , L_{+2} , L_{+3} ; R_{ctrl} was the reference for R_{pert} , R_{+1} , R_{+2} and R_{+3} .

The exact onset of the perturbation was visually determined as the time at which the ankle position and velocity curves of the perturbed step were differentiated from those of the corresponding control step. Each perturbation was assigned to a timing group corresponding to one fifth of the step duration: 0–20% (t1), 20–40% (t2), 40–60% (t3), 60–80% (t4) or 80–100% (t5) (Fig. 1C). In total 441 perturbations were analyzed with the following repartition: $n = 74, 57, 80, 101$ and 129 for respectively t1, t2, t3, t4 and t5. The perturbation was in addition characterized by its rise time (ms), amplitude (°), average speed (° s⁻¹) and hold time (ms) (see Fig. 2A).

The ground reaction force signals (F_y and F_z) were Butterworth first-order low-pass filtered at a cutoff of 40 Hz; the data were passed through the filter in both directions to avoid any phase lag. F_x was not studied.

Contact and flight phases were visually determined from F_z traces to obtain the contact (t_c , ms), flight (t_f , ms) and total (T , ms) durations of each step (see Fig. 1C). The maximal amplitude of the negative fore-aft ($F_{y,\text{brake}}$, N), of the positive fore-aft ($F_{y,\text{push}}$, N) and of the vertical ($F_{z,\text{max}}$, N) GRFs was measured. The step length (L_{step} , mm) was calculated as T multiplied by the averaged treadmill speed during T . During heel-toe running, which is the most used running technique by our subjects, a distinct vertical impact peak can be detected in the first 50 ms of a step. The amplitude ($F_{z,i}$, N) and the time ($t_{z,i}$, ms) of this impact peak were measured when present. The mean loading rate ($G_{z,i}$, N ms⁻¹) was calculated as the ratio of $F_{z,i}$ divided by $t_{z,i}$.

2.5. Statistics

For each parameter, the value measured at any step after the perturbation was compared to its value in the corresponding control step. The difference was calculated and compared to zero with a one-sample Student's t test ($\alpha = 0.05$).

which the ankle joint was locked in its position (plateau). The absolute amplitude of the perturbation (3) corresponds to the ankle angular displacement measured during the rise time. The relative amplitude (4) was obtained by subtracting the ankle angular displacement of the control step L_{ctrl} from the absolute amplitude of the perturbation. The absolute speed was calculated as $(3)/(1)$. Panel B shows for each timing group t1–t5 the relative right ankle dorsiflexion at specific times after the perturbation: at the end of the rise time (grey bar) and at the following toe-offs and touch-downs (L_{pert} TO, R_{pert} TD, R_{pert} TO and L_{+1} TD; black bars) as indicated. The values are expressed as the difference between the right ankle position at these specific times and its position at the corresponding time of the control step. Bars represent mean $\pm$ S.D. For t1 to t5 the arrow shows the mean value of the perturbation onset. Note the time scale is the same in Panels A and B. *Significant difference from 0 ($p < 0.05$).

3. Results

We did not observe any fall, and all the subjects continued to run normally, in spite of the ankle perturbations.

3.1. Effect of the perturbation on the right ankle angle

The perturbations were quite similar between timing groups (t1–t5, Fig. 2A); the average right ankle dorsiflexion was characterized by a rise time of 43 ± 9 ms, an absolute amplitude of $9.0 \pm 3.5^\circ$, an absolute speed of $206 \pm 66^\circ \text{ s}^{-1}$ and an hold time ≈ 100 –150 ms. An example is illustrated for a t2 perturbation in Fig. 2A. The mean delay between the perturbation and the R_{pert} TD is 327 ± 28 , 252 ± 26 , 181 ± 24 , 113 ± 22 and 45 ± 16 ms for respectively t1, t2, t3, t4 and t5. The relative amplitude of the perturbation decreased slightly from t1 to t5 but was not significantly different between timing groups (from 7.9° to 5.3° , Fig. 2B; grey bars).

The right ankle angle was measured at different moments after the perturbation (L_{pert} TO, R_{pert} TD, R_{pert} TO and L_{+1} TD) and was compared to the values obtained during the control stride (Fig. 2). For t1 and t2, we observed a dorsiflexion increase only at L_{pert} TO (2.4° and 5.2° , respectively). For t3, the increase was 6.3° at L_{pert} TO and still 2.4° at R_{pert} TD. For t4, the right ankle dorsiflexion increased by 2.2° at L_{pert} TO and by 5.6° at R_{pert} TD. For t5, in which the perturbations were evoked after L_{pert} TO, the dorsiflexion ankle

angle was increased by 4.8° at R_{pert} TD. For t4 and t5, the right ankle dorsiflexion was still slightly increased at R_{pert} TO and L_{+1} TD compared to control steps. So, perturbations of late timing (t4 and t5) had a longer lasting effect on the right ankle angle than perturbations of early timing (t1 and t2).

3.2. Immediate effect of the perturbation on the running pattern (R_{pert} and L_{+1} , Table 1)

There seemed to be a time-dependent effect of the perturbation on the following first two steps (R_{pert} and L_{+1}): the shorter the delay between the perturbation and the right TD (groups t4 and t5), the greater the number and the size of significant modifications.

In group t1, none of the measured parameters was significantly modified during R_{pert} . During L_{+1} , few small significant modifications were observed.

In group t2, t_c , T and L significantly increased and $F_{z,\text{max}}$ decreased during R_{pert} . During L_{+1} , L and $F_{y,\text{push}}$ decreased and $F_{z,i}$ increased.

In group t3, T and L significantly increased and $F_{z,\text{max}}$ decreased during R_{pert} , as was observed for t2. During L_{+1} , $t_{z,i}$, t_c and $F_{z,i}$ increased.

In group t4, beside a small increase of t_c , we observed larger modifications (more than 10%, see **bold** in Table 1) in the vertical impact peak during R_{pert} ; on an average the peak occurred 5 ms

Table 1
Significant adjustments observed during the first seven steps following the perturbation.

Parameter unit	$t_{z,i}$ ms	t_c ms	t_f ms	T ms	L mm	$F_{y,\text{brake}}$ N	$F_{y,\text{push}}$ N	$F_{z,i}$ N	$F_{z,\text{max}}$ N	$G_{z,i}$ N ms ⁻¹
R_{pert}	t1	–	–	–	–	–	–	–	–	–
	t2	–	3 ± 10	–	4 ± 9	9 ± 32	–	–	-25 ± 84	–
	t3	–	–	–	3 ± 11	10 ± 37	–	–	-22 ± 84	–
	t4	5 ± 5	2 ± 10	–	–	–	–	-97 ± 163	–	-7 ± 7
	t5	4 ± 6	4 ± 9	-7 ± 12	-3 ± 11	–	-11.8 ± 41.2	12.0 ± 41.1	-155 ± 141	-7 ± 6
L_{+1}	t1	3 ± 4	3 ± 8	–	3 ± 8	9 ± 29	–	–	–	-3 ± 6
	t2	–	–	–	–	-8 ± 29	–	-9.5 ± 29.2	40 ± 77	–
	t3	2 ± 4	4 ± 11	–	–	–	–	45 ± 99	–	–
	t4	3 ± 5	6 ± 10	-3 ± 12	4 ± 11	–	10.3 ± 34.3	-11.6 ± 38.4	45 ± 115	-2 ± 7
	t5	1 ± 4	6 ± 11	-3 ± 12	3 ± 10	14 ± 37	15.8 ± 36.2	-7.8 ± 35.3	–	-21 ± 62
R_{+1}	t1	–	–	–	–	–	–	–	18 ± 71	–
	t2	–	–	–	–	–	–	-39 ± 94	–	-2 ± 5
	t3	–	–	–	–	–	–	–	-19 ± 72	–
	t4	–	4 ± 9	-3 ± 10	–	–	–	-37 ± 140	–	–
	t5	–	–	–	–	–	–	–	-16 ± 74	–
L_{+2}	t1	2 ± 4	–	–	–	–	-12.7 ± 34.3	–	–	-2 ± 6
	t2	–	–	–	–	–	–	–	–	–
	t3	3 ± 4	4 ± 10	–	–	–	–	-33 ± 81	–	-4 ± 5
	t4	2 ± 4	4 ± 9	-6 ± 12	–	-8 ± 37	-8.5 ± 35.5	–	–	-2 ± 6
	t5	–	4 ± 10	-4 ± 13	–	–	–	–	–	–
R_{+2}	t1	–	–	–	–	–	–	–	–	–
	t2	–	–	–	–	–	–	–	–	–
	t3	–	–	–	–	–	–	–	–	–
	t4	–	2 ± 10	–	–	–	–	–	–	–
	t5	–	–	-3 ± 12	–	–	-11.4 ± 33.8	–	-15 ± 80	–
L_{+3}	t1	2 ± 4	3 ± 9	–	–	–	–	–	–	–
	t2	–	–	–	–	–	–	–	–	–
	t3	3 ± 4	4 ± 10	-3 ± 12	–	–	–	–	–	-3 ± 7
	t4	3 ± 4	4 ± 9	-4 ± 12	–	–	–	–	–	-3 ± 6
	t5	–	4 ± 10	-4 ± 13	–	–	–	–	–	–
R_{+3}	t1	–	–	–	–	–	–	–	–	–
	t2	–	–	–	–	–	–	–	–	–
	t3	–	2 ± 8	–	3 ± 8	9 ± 29	–	–	–	–
	t4	–	2 ± 10	–	–	–	–	–	–	–
	t5	–	–	–	–	–	-6.9 ± 32.6	–	–	–

The values are expressed as the difference between the mentioned step and the corresponding control step (R_{ctrl} or L_{ctrl}). The table shows the mean $\pm$ S.D. of the differences only if they are significantly different from 0 ($p < 0.05$). The parameters are defined in Section 2. Modifications greater than 10% are in **bold**; the % increase was calculated as $100 \times (\text{experimental value} - \text{control value}) / \text{control value}$. Note that two subjects were excluded from the vertical impact peak analysis ($t_{z,i}$, $F_{z,i}$ and $G_{z,i}$) because they did not run with a distinct heel strike.

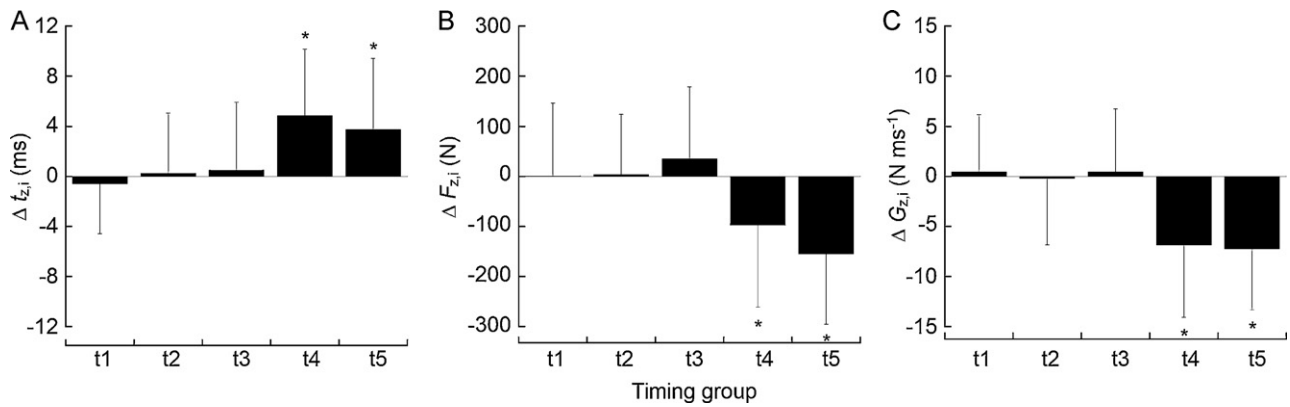


Fig. 3. Effects of the perturbation for each timing group on the following right foot impact parameters: $t_{z,i}$ (ms, Panel A), $F_{z,i}$ (N, Panel B) and $G_{z,i}$ (N ms⁻¹, Panel C). The results are expressed as the difference between the parameter value in the perturbed step and its value in the corresponding control step. *Significant difference from 0 ($p < 0.05$).

later with a decreased amplitude of 97 N resulting in a reduction of its loading rate by 7 N ms⁻¹ (Fig. 3). During L_{+1} , there were many significant modifications but none were greater than 10%: $t_{z,i}$, t_c and T increased and t_f decreased. The forces applied by the subject against the ground were also modified; in the fore-aft direction, $F_{y,brake}$ increased and $F_{y,push}$ decreased; in the vertical direction, $F_{z,i}$ increased and $G_{z,i}$ slightly decreased.

In group t5, the same strong modification (more than 10%) of the vertical impact peak was observed during R_{pert} step: $t_{z,i}$ increased, $F_{z,i}$ and $G_{z,i}$ decreased (Fig. 3). There were many other smaller modifications: T decreased with a decrease t_f and an increase t_c . $F_{y,brake}$ decreased, $F_{y,push}$ increased. During L_{+1} , there were also many small but significant modifications: $t_{z,i}$, t_c , T and L increased and t_f decreased. As in the t4 group, $F_{y,brake}$ increased and $F_{y,push}$ decreased. In addition, $G_{z,i}$ and $F_{z,max}$ decreased.

3.3. Late effect of the perturbation on the running pattern (R_{+1} to R_{+3} , Table 1)

The modifications observed later (after the first two steps) were small and disperse. They occurred more often on the left steps than on the right steps. The most affected parameter was t_c , which was always increased during the left steps L_{+2} and L_{+3} in groups t3, t4 and t5. On the other hand, T and L were two stable parameters. Indeed, T was modified only during R_{+3} for t3, and L during R_{+3} for t3 and during L_{+2} for t4. The significant modifications of the vertical impact peak were small and infrequent.

4. Discussion

An important result coming from our experiments is that in all cases subjects continued to run normally after the perturbation. They were able to rapidly adjust their running pattern to maintain their stable progression on the treadmill. This ability has already been observed in animal running after an unexpected perturbation [13–16] and was called dynamic stability [17,18].

Our perturbation was evoked on the right ankle during its swing phase. We observed immediate and late adjustments, respectively occurring during the first two steps following the perturbation (R_{pert} and L_{+1}), and during the next five steps (R_{+1} to R_{+3}).

4.1. Immediate adjustments

In order to maintain their running pattern, the subjects realized many small but significant adjustments to their first two post-perturbation steps. (1) The step length and the step period were quite stable. When both were modified, they varied in the same direction, which is functionally important to continue running at the

speed imposed by the treadmill and consequently to avoid falling. An increase in the step period was associated with a delayed vertical impact peak, and a longer contact time not compensated by a reduced flight time. (2) The strongest modifications of the vertical component of the GRFs concerned the impact of the foot, specifically for the perturbations of late timing (t4 and t5). (3) Finally, modifications of the fore-aft component of the GRFs were observed principally when the perturbations were evoked just before the foot contact (t4 and t5). During R_{pert} , the subjects exerted a smaller maximal braking force and pushed off with a greater maximal force. By contrast, during the next step (L_{+1}) subjects exerted a greater maximal braking force and pushed off with a smaller maximal force. Thus subjects seemed to adjust the fore-aft component of the GRF to deal with the perturbation. This component, although considered essential to the understanding of the biomechanics of normal running [21,22], has been much less studied than the vertical component in experiments on perturbed locomotion, and would seem to deserve more attention in the future.

The adjustments observed in the first two steps following the perturbation seem to be time-dependent. The longer the delay between the perturbation and the next TD, the less frequently the adjustments were observed in the first two steps. This is shown most clearly in the first step R_{pert} : no biomechanical modification was observed in R_{pert} when the delay was on average 327 ms (t1). The modifications were limited when the delay was on average 252 and 181 ms (respectively t2 and t3). When the delay was shorter (on average 113 and 45 ms for respectively t4 and t5), many significant biomechanical modifications were observed. In human walking, Weerdesteyn et al. [6], reported that the first reactions to avoid an obstacle occurred at short latencies; the differentiated acceleration curve of the foot deviated from the control by 122 ms on average after the appearance of an obstacle. In our study, in groups t1, t2 and partially t3, the delay seemed to be long enough for the system to realize the needed adjustments before the next touch-down.

When the perturbation was evoked just before the right step touch-down (t4 and t5), we observed an increased ankle dorsiflexion at R_{pert} TD associated with a strongly delayed and reduced vertical impact peak force, along with a decreased loading rate. To further investigate the relationship between ankle position at TD and vertical impact, we tested the correlations between the two. As expected, a greater dorsiflexion at TD was correlated with a delayed vertical impact peak (Fig. 4A) whose amplitude (Fig. 4B) and loading rate (Fig. 4C) were reduced. All three curve fit slopes were significantly different from 0 ($p < 0.05$) with low r^2 (respectively 0.22, 0.10 and 0.23). Together, these results indicated that the ankle position at TD was one of the factors likely to explain the observed modifications to the vertical impact.

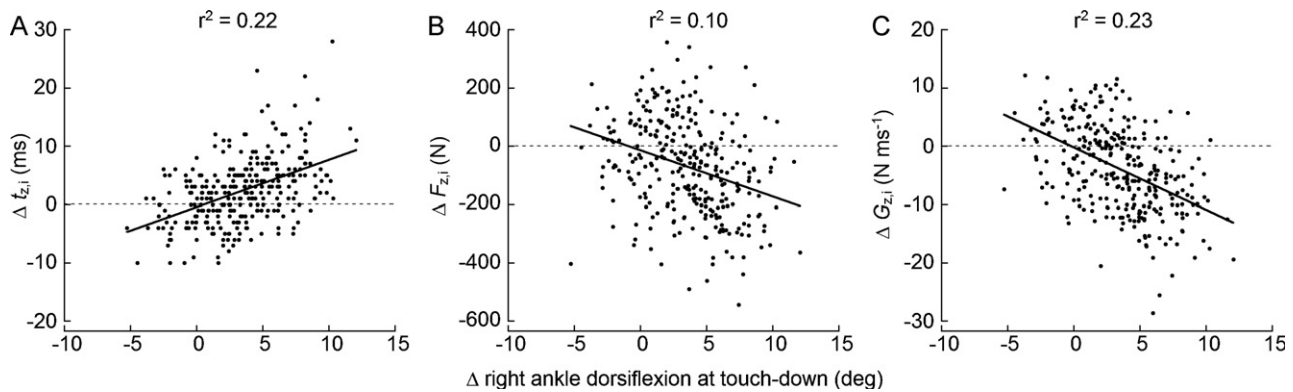


Fig. 4. Variation of the vertical force impact peak time $t_{z,i}$ (ms, Panel A), amplitude $F_{z,i}$ (N, Panel B) and mean loading rate $G_{z,i}$ (N ms^{-1} , Panel C) as a function of the variation in the right ankle dorsiflexion at touch-down (right TD). Data from all traces showing a distinct heel-strike are plotted from all timing groups (t1–t5, $n = 307$). The least-squares linear curve fits presented on each plot are significantly different from 0 ($p < 0.05$). The coefficient of determination (r^2) is indicated at the top of each figure. The results are expressed as the difference between the parameter value in the perturbed step and its value in the corresponding control step. *Significant difference from 0 ($p < 0.05$).

The effect of ankle position at TD on the vertical impact peak has been observed previously. Using a modeling approach to normal human running, Gerritsen and colleagues [23] showed that at TD an increased angle between the shoe sole and the ground (corresponding to an increased ankle dorsiflexion if the lower leg position is not modified) decreased the amplitude as well as the loading rate of the vertical impact peak. In an experimental study comparing bare-foot and shod running, De Wit et al. [24], observed in the shod condition a greater ankle dorsiflexion at TD associated with a delayed vertical impact peak and a decrease of the loading rate. Other factors at TD, not measured in our study, such as the leg angle [23], the knee angle [24,25], the vertical speed of the heel [23] or of the shank segment [26], could also influence the vertical impact. In fact, the overall geometry at TD could induce a succession of *passive regulations* [11,27] like those observed on the vertical impact. In such a passive regulation system, it may be sufficient, as suggested by Daley [17], to check the foot placement or the leg stiffness only at critical moments (TD or TO, for example) in order to prepare for the next step. In our study, however, the modified ankle position resulted from a perturbation and therefore we cannot exclude the possibility that some of the observed adjustments were induced by an active regulation of the leg muscle activity. It would be interesting to study the electromyographic responses to see whether a modification of the leg muscles activation could also partially explain the modifications of the impact of the foot against the ground. In walking Shinya et al. [7] have observed an ankle muscular reflex co-contraction after an unexpected perturbation (drop) and suggested that this response could contribute to the absorption of the impact on the ground by stiffening the ankle joint.

4.2. Late adjustments

There were still a few small but significant modifications during the steps following L_{+1} (R_{+1} to R_{+3}). These late adjustments probably contributed to maintain the step length and the step period as constant as possible. The stability of these two parameters allowed the subject to continue running at the speed imposed by the treadmill without stumbling or falling. Another interesting observation was that the late adjustments predominantly occurred on the left steps, which could have been perceived by the subjects as being more 'secure' since the perturbation could only occur on the right ankle, the only one equipped with the exoskeleton.

In conclusion, this innovative study using a powered ankle-foot exoskeleton shows that humans are able to maintain their running

pattern after a mechanically evoked ankle dorsiflexion. This perturbation, whatever its timing during the swing phase, modified the right ankle position and induced some time-dependent modifications of the running pattern. It is still not clear whether these modifications resulted from a passively modified ankle and leg geometry at touch-down, or were at least partly the result of an active regulation. To sort this out, the leg muscles' electromyographic responses to such perturbations could be investigated together with the biomechanical running pattern adjustments.

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Conflict of interest statement

None of the authors have financial or other conflicts of interest in regard to this research.

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