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Short communication

Humans adjust the height of their center of mass within one step when running across camouflaged changes in ground level

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ABSTRACT

In running, humans use different control strategies that are most likely influenced by environmental conditions. For example, when human runners face a change in ground level, they adapt the height of their center of mass (CoM) in preparation. In a situation in which a drop might occur but without visual cues regarding its actual height, such a preparation is not possible. We here used camouflaged drops (which occurred by chance) as mechanical disturbances and analyzed the adaptations in the vertical oscillation of the runners CoM. We found that humans lowered their CoM by about 25% of the possible drop height in preparation for the camouflaged contact, regardless of whether a drop occurred or not. In flight phase following the disturbance, the CoM was lowered by about 90% of the drop height in the case of the camouflaged drop and remained almost unaffected (+5%) in the case of level ground. Thus, runners resort to a CoM-control strategy with a fixed desired trajectory height in the flight phase following the camouflaged ground contact. In contrast to previously reported results which show that visible ground level changes were compensated within several steps, this strategy compensates ground level disturbances instantly within a single step.

1. Introduction

In running, humans use different control strategies that are most likely influenced by environmental conditions, e.g. runners increase their step length over a sidewalk curb (Larsen et al., 2016), they adjust their leg stiffness to accommodate surface stiffness (Ferris et al., 1998; Kerdok et al., 2002) and vertical steps (Grimmer et al., 2008; Müller and Blickhan, 2010; Müller et al., 2010) or they adapt their leg length and orientation in preparation of visible and camouflaged drops (Müller et al., 2012). All of these strategies share a common goal: to control the trajectory of the center of mass (CoM).

One approach during running on uneven ground could be to maintain the global CoM trajectory independent of the occurrence of upward steps or downward drops, i.e. there is adaptive lifting or lowering of the CoM with respect to the instant ground level but not with respect to the global coordinate system. Simulations revealed that this goal can be achieved by using the flight phase to set the correct parameters of the system at the instant of touchdown (Ernst et al., 2009; Koepl and Hurst, 2011; Palmer and Eaton, 2014). A contrasting strategy is to compensate the disturbance height within a single step and keep the local height of the CoM with respect to the instant ground level constant but not the global one. This can be interpreted as a deadbeat control of the CoM with a desired local trajectory (apex) height as control goal (Hutter et al., 2010; Saranli et al., 1998). It was shown that such a strategy can be implemented in a feedforward manner controlling the system parameters (e.g. spring stiffness and orientation) in flight phase and that it optimizes self-stability (Ernst et al., 2012; Seyfarth et al., 2002; Wu and Geyer, 2013).

Besides these theoretical investigations, experimental studies exist analyzing the CoM-adaptation strategies in humans and birds during running on uneven ground. In preparation of visible perturbations humans adapt the height of their CoM by lifting it about 50% of step height or by lowering it about 40% of drop height (Blickhan, et al., 2013; Ernst, et al., 2014). Thus, the visual perception allows humans to prepare for it actively. Interestingly, a similar strategy can be observed in birds. Comparable to humans, birds adjust their leg and body mechanics in anticipation of a visible upward step and achieve a relatively steady CoM trajectory within the step (Birn-Jeffery and Daley, 2012). However, when running birds encounter instead of a visible step a visible or unexpected

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drop, CoM adaptation strategy seems to be different. Most of the change in potential energy occurred during the stance phase of the perturbed contact, not during the step ahead of the disturbance, regardless of whether it is visible or not (Daley and Biewener, 2006). Unlike birds, it seems that humans use a compromise during running over a camouflaged drop, which primarily helps them to cope with the surprising drop but also avoid having to adjust poorly if no drop occurs (Müller, et al., 2012). Nevertheless, the CoM adaptation strategies in humans when encountering a camouflaged drop have not yet been described.

The aim of this study is to analyze the vertical adaptation of the runners' CoM height while running over camouflaged drops (which occur by chance) and to consider what underlying CoM control strategies runners utilize after encountering the disturbance.

2. Methods

The experimental methods were presented by Müller et al. (2012), hence we briefly report the setup and measurement below. Whereas this previous paper focused on leg parameters, the present study analyzes changes in CoM height.

Eleven healthy subjects were instructed to run along a 17 m runway with two consecutive force plates embedded in its center. The second force plate adjustable in height served as a single drop (Fig. 1). After subjects had run on the unperturbed flat track (VL; Visible Level), the force plate at the second contact was lowered by −50 mm and −100 mm. After these visible trials, the force plate at the second contact was camouflaged and set initially to −100 mm for the first run. Subsequently the elevation was randomly set to 0 mm (CL; Camouflaged Level) or −100 mm (CD10; Camouflaged Drop). In total, runners had to perform at least 21 camouflaged runs in a row (9 × CD and 12 × CL) without knowing whether a drop occurs or not.

Kinematics was recorded using a three dimensional infrared system (MCU 1000, Qualisys, Gothenburg, Sweden) with reflective markers placed among others on L5, C7 and on both sides of trochanter major. The kinematic data were filtered with a third-order low-pass Butterworth filter (40 Hz cut-off frequency). Following the method described in Ernst et al. (2014), the vertical extrema of three steps in sequence (min_1, max_1, min_2, max_2, min_3, max_3; Fig. 1) were used as (time) reference points to investigate the adaptation process in the different phases. For analysis, we chose all those trials of each subject that were distributed in a narrow range of their preferred running speed achieving steady-state running (difference of horizontal speed between max2 and max3 < 5%). As estimate of the relative vertical adaptation of the CoM (Δy) we used the mean of the adaptations of three markers – L5, C7, and hip (the mean of the right and left trochanter major; (Ernst et al., 2014)). In general, Δy in an extremum is given by the difference between the absolute vertical positions of the camouflaged (CL, CD) and the undisturbed (VL) situation.

The relative vertical adaptations of the CoM (Δy) were expressed as mean ± standard deviation over all trials and all subjects as well as for all trials of the single subjects. The influence of the different setups on Δy were statistically tested (i.e. Δy (VL) to Δy (CL) and Δy (VL) to Δy (CD)) as well as between the camouflaged setups (i.e. Δy (CD) to Δy (CL)). When the assumption of the normal distribution (Lilliefors test) or the homogeneity of variances (Bartlett multiple-sample test) was not fulfilled, a nonparametric test (Kruskal-Wallis) was performed. Otherwise, a one-way ANOVA was used. To specify the differences within a group post-hoc tests were used. The statistics were performed with the Statistics Toolbox of Matlab (R2009b Mathworks Inc., Natick, MA, USA).

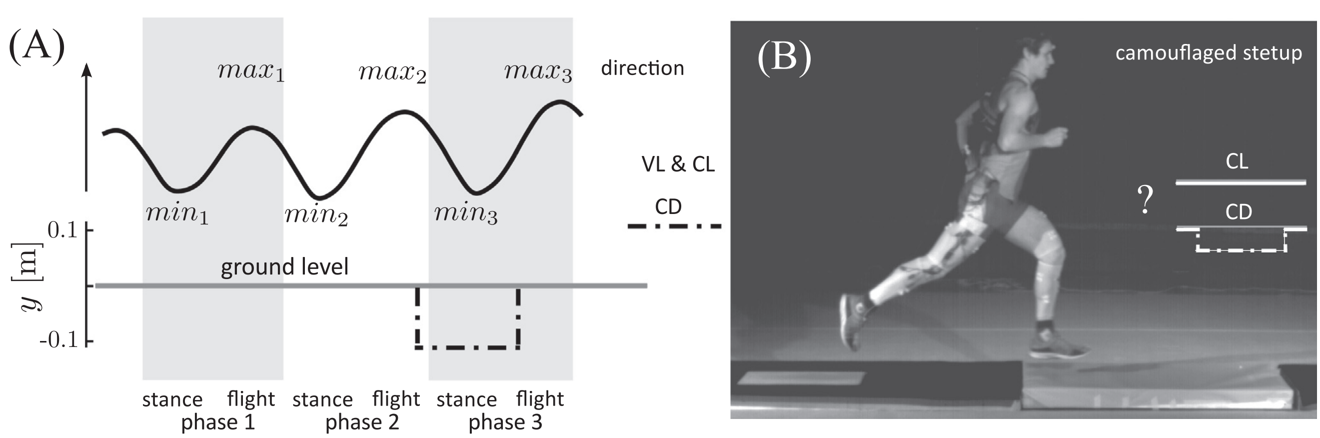

Fig. 1. Schematic illustration of a vertical CoM trajectory and the runway. (A) show a CoM trajectory together with the investigated vertical extrema (i.e. minima and maxima) while facing the ground disturbances (below). (B) Shows a runner in flight phase 2 for the camouflaged setup. Two different situations occur by chance: a camouflaged flat ground (white line: CL) or a camouflaged drop of 10 cm (dashed-dotted white line: CD). Note that the photo is flipped horizontally. The ground contact stance phase 3 (on the perturbed step) was always with the right leg.

Table 1
Relative vertical adaptation Δy for the different extrema and setups. The mean values and standard deviations are given in [mm]. Statistical differences to the reference (VL) are written bold ($p < 0.05$). Such differences can be observed in max_2, min_3, max_3 for both setups except for max_3 of CL. Statistical differences between the camouflaged setups (CD and CL) are marked with '*' ($p < 0.05$). Such differences can be observed in min_3 and max_3. N: minimum number of valid trials per setup. VL values are zero, see method and Fig. 2B.

Setup	Δy	min_1	max_1	min_2	max_2	min_3	max_3
CD (N > 81)		−3 ± 12	−2 ± 16	−1 ± 11	**−29 ± 18**	**−64 ± 13***	**−92 ± 22***
CL (N > 115)		−4 ± 11	−2 ± 16	0 ± 12	**−27 ± 17**	**−12 ± 15***	6 ± 20*

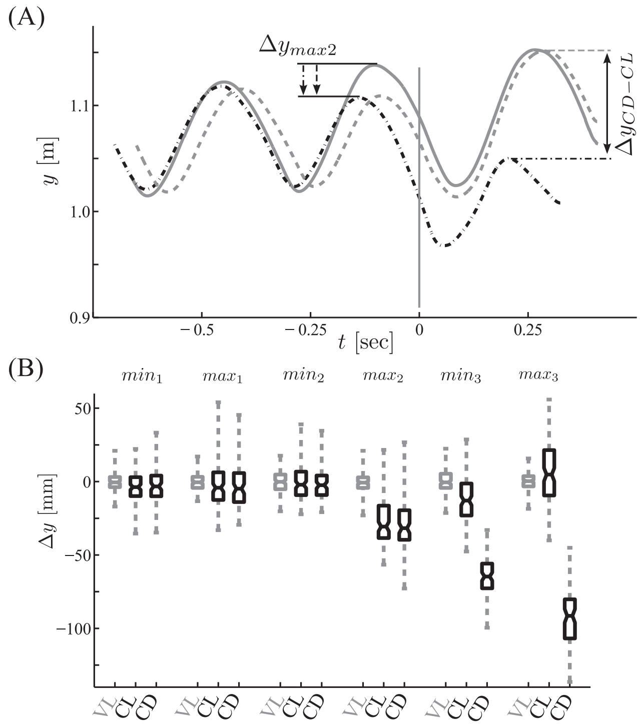

Fig. 2. Vertical oscillation of the body's CoM while running across a camouflaged ground level change. The trajectory of the CoM (A; CL - dashed grey line; CD - dashed-dotted black line, VL - solid grey line) and the relative vertical adaptation Δy of the CoM (B). The CoM was lowered equally in preparation of a camouflaged incidental drop whether a drop occurred or not (max2). In the subsequent extrema the CoM height depends on the situation (min_3 & max_3). (B) The values of the lower quartile, median, and upper quartile are given over all subjects and trials (black boxes) including the reference (grey boxes). The whiskers (grey dashed lines) represent the range of the adaptations including all single trials. t = 0 (vertical grey line): touch down on the perturbation (start of stance phase 3).

3. Results

In preparation of camouflaged contacts (max_2) runners lowered their vertical CoM height by the same amount whether a drop occurred (−29 mm) or not (−27 mm; Table 1, Fig. 2B). However, compared to the latter mean values we found that runners lowered their CoM in front of the camouflaged contact even more for the first time they encountered the CD situation (all subjects except p#11, Table 2).

In case of hitting the camouflaged level ground, the runners' vertical CoM was slightly lowered (Δy_{min3} = −12 mm) and almost the same as for level running in the subsequent flight phase (Δy_{max3} = 6 mm; Table 1). In case of hitting the camouflaged drop, runners lowered their CoM during ground contact (Δy_{min3} = −64 mm) and in the subsequent flight phase (Δy_{max3} = −92 mm).

In the flight phase after the camouflaged contact (max_3) the height difference between CL and CD was 98 mm. Looking at the individual CD-adaptations at max_3 (Δy_{max3}) we found adaptations ranging from −69 mm (p#1, minimum) to −111 mm (p#8, maximum). The range of the height differences between CL and CD was smaller, ranging from 86 mm (p#3, minimum) to 113 mm (p#8, maximum; Table 2, Fig. 3). Compared to the latter mean values of all trials, the range of the height differences between CL and CD was greater for the first time they encountered both situations, ranging from 47 mm (p#2, minimum) to 133 mm (p#11, maximum; Table 2).

4. Discussion

Confronted with ground level disturbances in their path human runners adapt their leg parameters not only during the disturbed contact but also in advance (Larsen et al., 2016; Müller and Blickhan, 2010; Müller et al., 2012). These adaptations can change the height of the CoM with respect to the instant ground level and achieve a smooth, not abruptly changed trajectory of the CoM (Ernst et al., 2014). For example, visible ground level changes of up to 15 cm were compensated within two to three steps (Fig. 5B–D). In contrast to visible ground level changes, a camouflaged drop seems to be compensated instantly within a single step.

The pre-adaptation of the CoM in front of the camouflaged contact matches a corresponding adaptation for a visible −70 mm drop (assuming a 40% adaptation in front of a drop, Fig. 4A). This

Table 2
Subject-specific relative vertical adaptation Δy for the camouflaged setup and the extrema max_2, min_3, max_3. The values of the first trial for CL and CD, i.e. when the subject experienced a camouflaged level and camouflaged drop at the first time, are given below the subjects mean values. Second column shows the individual initial leg length (l_0) and last column shows the difference between CL and CD for max3. All values are given in [mm].

Subject		max_2	min_3		max_3		max_3	
	l_0	CL	CD	CL	CD	CL	CD	CL-CD
p#1	862	−14 ± 6	−17 ± 12	−3 ± 8	−57 ± 8	28 ± 14	−69 ± 17	97 ± 22
1st		−23	−20	−16	−65	56	−60	116
p#2	886	−29 ± 13	−33 ± 9	9 ± 11	−51 ± 5	16 ± 13	−79 ± 12	95 ± 17
1st		−52	−38	−11	−56	−19	−66	47
p#3	794	−33 ± 9	−32 ± 14	−7 ± 5	−61 ± 8	−19 ± 11	−105 ± 16	86 ± 20
1st		−36	−58	−13	−77	−12	−91	79
p#4	879	−36 ± 11	−44 ± 11	−14 ± 11	−75 ± 8	−8 ± 18	−96 ± 15	88 ± 24
1st		−46	−66	−18	−81	−5	−86	81
p#5	933	−35 ± 9	−37 ± 9	−15 ± 4	−66 ± 5	−5 ± 8	−103 ± 13	98 ± 15
1st		−54	−47	−20	−76	−2	−89	87
p#6	909	0 ± 16	1 ± 16	−15 ± 13	−57 ± 11	−27 ± 7	−75 ± 18	102 ± 19
1st		−31	−20	−36	−58	39	−62	101
p#7	884	−32 ± 9	−37 ± 11	−16 ± 5	−73 ± 6	−1 ± 12	−97 ± 14	96 ± 18
1st		−30	−42	−13	−84	−5	–	–
p#8	971	−36 ± 13	−33 ± 7	−21 ± 9	−70 ± 7	2 ± 20	−111 ± 24	113 ± 32
1st		−47	−38	−36	−85	32	−66	98
p#9	1005	−43 ± 8	−45 ± 14	−33 ± 8	−84 ± 10	5 ± 11	−95 ± 8	100 ± 14
1st		−43	−73	−31	−100	24	−82	106
p#10	862	−34 ± 5	−29 ± 6	−27 ± 6	−68 ± 5	−2 ± 21	−109 ± 20	107 ± 29
1st		−34	−34	−29	−62	34	−85	119
p#11	923	−2 ± 12	−3 ± 19	10 ± 6	−39 ± 6	25 ± 10	−72 ± 25	97 ± 27
1st		19	27	13	−37	24	−109	133

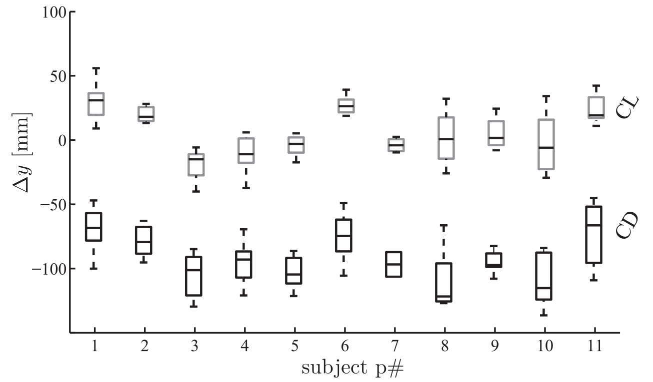

Fig. 3. Relative vertical adaptation Δy for the camouflaged setup at max_3 for all single subjects. The difference between CL and CD is almost the drop height (100 mm) for every subject independent of the inter-individual variations in CL and CD. The values of the lower quartile, median, and upper quartile are given over all trials of a single subject (CL - grey boxes, CD - black boxes).

pre-adaptation can be attributed to the experimental setup. In our experiments the perturbed contact was camouflaged but expected (randomly set to an elevation of 0 mm or −100 mm; (Müller et al., 2016, 2012)). However, compared to the mean values subjects lowered their CoM in front of the camouflaged contact even more for the first time (Table 2). This suggests that they slightly adjust their pre-adaptation after they experienced the CL and/or CD situation for the first time.

In the subsequent flight phase after the camouflaged contact, the CoM height depends on the situation. When the runners encountered the camouflaged drop, the CoM was lowered by about the drop height and when instead the runners hit the camouflaged level contact they overshoot the level height slightly. Interestingly, the height difference between the two camouflaged situations (98 mm) equals almost the drop height (100 mm) independent of inter-individual variations in the adaptations to the single situations (Fig. 3, Table 2). Compared to this mean value, the average height difference between the first CL and CD trials is almost the same (97 mm) but show a larger range (Table 2). Moreover, after the first camouflaged trials most runners seem to adjust their strategy whereby the height differences approximate the drop height.

The adaptation of the runners' CoM height show that runners do not use strategies that keep the CoM at a constant global height (Ernst et al., 2009; Koepl and Hurst, 2011). In contrast, since the height difference is almost the drop height independent of inter-individual variations (Table 2 and Fig. 3) we assume that runners resort to a deadbeat control aiming for a desired CoM (apex) height during the expected but camouflaged contact. Such a control enables the runner to compensate the height disturbance within one step and therefore keep the current, local CoM height constant (the global CoM height is altered about height disturbance, Fig. 5A).

If runners would utilize a CoM deadbeat control aiming for a desired (apex) height through appropriate leg parameter adaptations, there would be no need to lower the CoM in front of the disturbance. Nevertheless, the pre-adaptation might shift the operating range to keep the parameters in a physiological range (GRF, global leg parameter). This might explain why humans lowered their CoM in front of a camouflaged disturbance even more for the first time they experienced the situation.

Why humans adjust their CoM height within one step when running across camouflaged changes in ground level and whether they use it in real life (e.g. while running across a bumpy meadow with high grass) is still unknown. In particular it remains partly uncertain if the observed strategy is a specifically tuned control for the given experimental setup or a more general control scheme. On the one hand we found the same outcome for the first trials and entire test (97 mm vs. 98 mm) on the other hand we see an individual tuning towards a "better" deadbeat control. One reason to use such a deadbeat control might be that it can be embedded in a feedforward manner by solely adapting leg orientation (Müller et al., 2012) and muscle pre-activation (Müller et al., 2015) during flight. However, the adjustment of the CoM height during running also depends on cognitive planning, learning, and other feedbacks (e.g. force-feedback). The contribution of these factors to the CoM

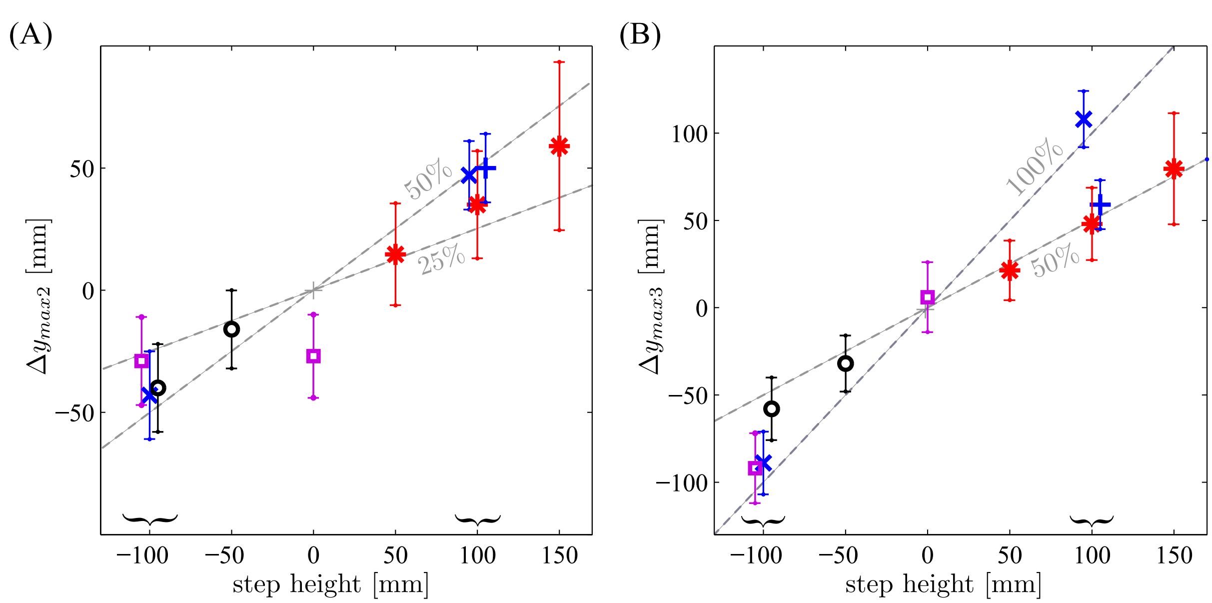

Fig. 4. Relative vertical adaptation of the CoM (Δy) for different step heights and situations. (A) Ahead of a ground level change (max_2) and (B) in the subsequent flight phase (max3). Magenta-squares - CD and CL (this study), black-circles - visible drops of −50 mm and −100 mm (Ernst et al., 2014; 50 mm evaluated additionally); red-asterisk – visible single steps of 50 mm, 100 mm and 150 mm (evaluated data from Grimmer et al. (2008)); blue-x – visible permanent ground level changes of 100 mm and −100 mm (Ernst et al., 2014); blue-cross visible single ground level changes of 100 mm (Ernst et al., 2014). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

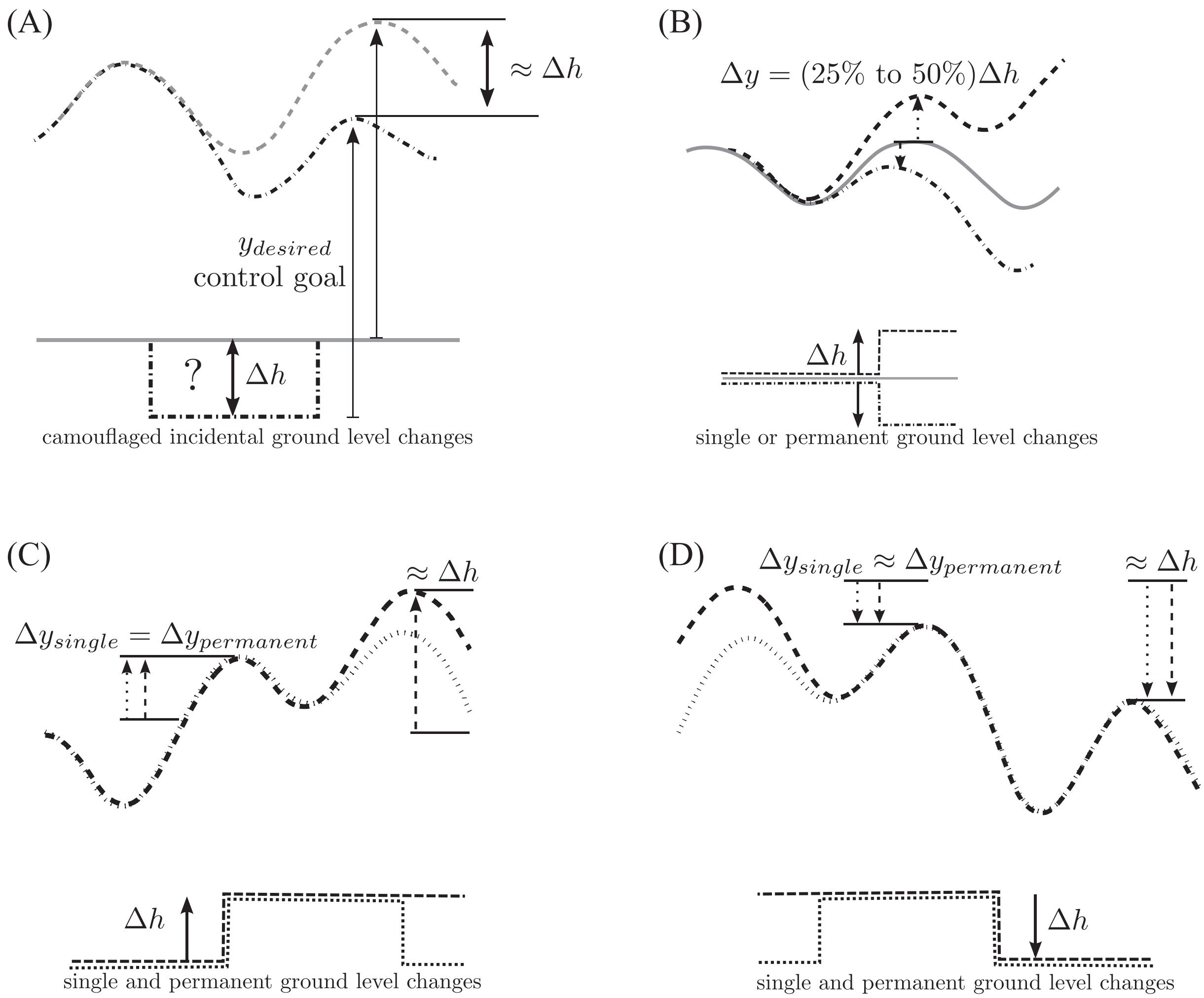

Fig. 5. General adaptation strategies of the CoM in human running. (A) Runners resort to a CoM deadbeat control adapting their subsequent flight height ($y_{desired}$) if they are confronted with camouflaged incidental ground level changes which they had experienced before (CL - dashed grey line; CD - dashed-dotted black line). For similar but visible ground level changes it was found that: (B) the adaptation in front of a ground level disturbance is about 25 to 50% of step height; (C) the adaptation in front of a visible ground level disturbance for single and permanent changes is of the same extent; (D) adaptations while leaving a single step are of the same size as the pre-adaptation for running down a step; (C) & (D) permanent ground level disturbances are compensated in the flight phase of the subsequent gait cycle (two steps to full compensation); with (C) & (D) it can be hypothesized that single ground level disturbances are compensated within three steps.

control strategies are important points that need to be addressed in future studies.

Conflict of interest statement

The authors declare that no financial and personal relationships with other people or organizations have inappropriately influenced the content of the work reported in this paper.

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