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The comparison of stepping responses following perturbations applied to pelvis during overground and treadmill walking

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Abstract.
BACKGROUND: Treadmills are used frequently in rehabilitation enabling neurologically impaired subjects to train walking while being assisted by therapists. Numerous studies compared walking on treadmill and overground for unperturbed but not also perturbed conditions.
OBJECTIVE: The objective of this study was to compare stepping responses (step length, step width and step time) during overground and treadmill walking in a group of healthy subjects where balance assessment robots applied perturbing pushes to the subject's pelvis in sagittal and frontal planes.
METHODS: During walking in both balance assessment robots (overground and treadmill-based) with applied perturbations the stepping responses of a group of seven healthy subjects were assessed with a motion tracking camera.
RESULTS: The results show high degree of similarity of stepping responses between overground and treadmill walking for all perturbation directions. Both devices reproduced similar experimental conditions with relatively small standard deviations in the unperturbed walking as well as in perturbed walking.
CONCLUSIONS: Based on these results we may conclude that stepping responses following perturbations can be studied on an instrumented treadmill where ground reaction forces can be readily assessed which is not the case during perturbed overground walking.

Keywords: Balance assessment robot, stepping responses, pelvis perturbations, treadmill walking, overground walking

1. Introduction

In everyday life we are faced with various situations during walking such as slipping, tripping, walking on uneven ground or adverse effect of external forces, which can lead to balance instability and may consequently result in a fall. Fall-related injuries are very common medical problems in elderly that predominantly occur during movement [1,2]. In addition, neurologically impaired subjects (e.g. after stroke, spinal cord injuries or other neurological diseases) have impaired locomotion abilities needing appropriate treatment. In rehabilitation centres such patients receive adequate training in order to improve their walking abilities, which may be done during walking overground (OG) or during walking on a treadmill (TM) with the assistance of physiotherapists [3–6].

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From the biomechanical perspective of dynamic balancing during human walking, center of pressure (CoP) has to oscillate around the floor projection of center of mass (CoM) while weight is shifted from one stance leg to the other. During walking we often need a series of corrective actions such as stepping as a response to unexpected external disturbances that move body CoM out of its nominal path [7–9]. Studying balance and investigation of its biomechanical strategies is often associated with perturbed actions during locomotion. Moving platforms under stance leg [10–12], external forces that act on body [13–16], slipping or tripping perturbations [17–20] are usually used techniques during OG or TM walking. From the perspective of gait assessment as well as rehabilitation, TM walking has numerous advantages compared to OG walking due to smaller needed area, controllable walking speed, larger volume of steps achieved and more repeatable measuring environment (electromyography, kinetics, kinematics). Furthermore, TM is more convenient for providing assistance from a therapist as a patient can also be equipped with the stationary body-weight support in order to walk safely [10,17,21].

Numerous studies have shown similarities as well as differences between OG and TM walking. Various spatiotemporal gait variables (e.g. stride length/time/velocity, cadence, gait subphases durations) were reported to be similar when comparing OG and TM walking. Lee at al. observed some differences in muscle activation patterns, joint moments and joint powers, but the overall patterns between OG and TM walking seemed similar [22]. In contrast, Hollman et al. reported that dynamic balancing during walking may need a certain degree of variability in spatiotemporal gait parameters and the lack of such variability, which was observed in TM walking, may impede motor performance [23]. Furthermore, assuming that the treadmill velocity is constant and subjects are familiarized with walking on a treadmill, gait kinematics and kinetics can be similar [22,24]. In gait balance studies, both TM and OG approaches are frequently used when applying perturbations, but there is a lack of studies that compare responses during OG and TM walking, especially where perturbations are applied to pelvis or torso in ML and AP directions. Demonstrating similarity in balancing responses following perturbations during OG and TM walking would be beneficial in particular in the clinical studies where the TM-based environment could be more convenient for training due to previously described reasons including fall-safe, less variable and controllable environment compared to OG-based environment. Another important limitation of OG-based balance studies is that the assessment of ground reaction forces is very limited and therefore mostly spatio-temporal gait parameters cannot be reliably assessed. However, since walking on TM differs from OG walking subject first needs to become acquainted with TM [27]. On the other hand, OG walking represents normal condition in daily life, where a subject can choose his natural walking speed.

The purpose of this study was to compare stepping responses resulting from perturbations applied to the pelvis in the anteroposterior (AP) and mediolateral (ML) directions during OG and TM walking in the same group of healthy subjects. The main goal was to investigate whether the resulting stepping responses are similar between the two walking environments which may have further implications for future dynamic balancing studies as well as walking training in rehabilitation that could be done to a greater extent on an instrumented treadmill.

2. Methods

2.1. Assessment devices

Balance Assessment Robots – OG-based (BAR-OG) and TM-based (BAR-TM) – were developed in our laboratory for the purpose of studying balancing responses during walking. The devices are identical in their mechanical design and control, consisting of two vertical rods connected with the pelvic link that

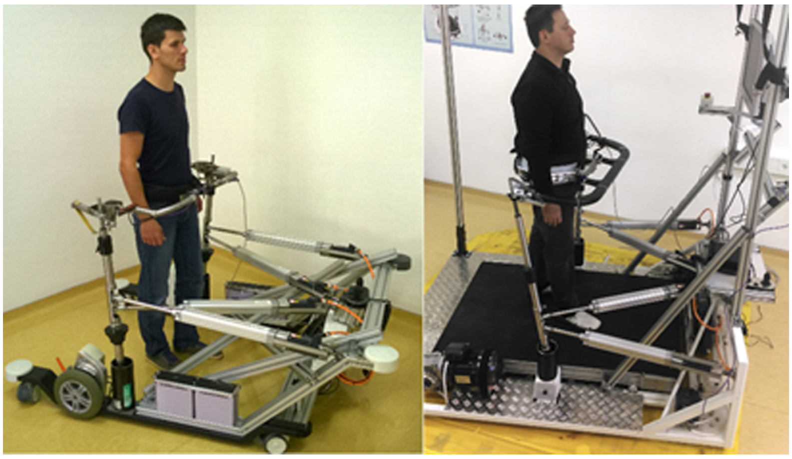

Fig. 1. Balance Assessment Robots for overground walking – BAR-OG (left) and treadmill walking – BAR-TM (right).

embraces subject's pelvis thus creating a parallel mechanism. The parallel mechanism is driven with 4 linear actuators (two on each side drive each vertical rod) and is admittance-controlled in order to provide free movement of subject's pelvis in 3 DoFs: ML displacement, AP displacement and rotation around pelvis' vertical axis, while the remaining DoFs (i.e. pelvis list, tilt, and vertical displacement along its vertical axis) are passive. The parallel mechanism can apply a desired force field around pelvis and/or impose perturbations to pelvis in any direction in transverse plane with force amplitude of up to 300 N. BAR-OG has a mobile platform with two castor wheels and two motorized wheels that are steered via operator's joystick, while BAR-TM contains a wide treadmill, which is placed between the vertical rods, beneath walkable surface. The devices are shown in Fig. 1: BAR-OG on the left [15] and BAR-TM on the right [25,26]. A detail description on BAR can be found in Olenšek et al. [15].

2.2. *Experimental setup and protocol*

Seven adult male volunteers, free from any musculoskeletal or neurological impairments and with no problems of balance, participated in the study (age: 33.4 $\pm$ 8.5 years, body mass: 80.1 $\pm$ 11.6 kg, height: 181 $\pm$ 5 cm). The subjects had no prior experience with the treadmill walking. Prior to measurements the subjects gave informed consent in agreement with the guidelines of the University Rehabilitation Institute institutional ethical committee.

A motion capture system Optitrack V120 Trio (NaturalPoint, Inc.) was used to capture the movement of the feet during the experiment. The V120 Trio camera was firmly mounted to the platform in front of the subject and directed to the subject's feet (shown in Fig. 1 on both BARs). Eight reflective markers were placed on both lower extremities (inner/outer side of ankle and two on the forefoot on each leg) and three reflective markers on the platform defining the local coordinate system. Each subject was first placed in the BAR-OG by embracing and tightening his pelvis with the pelvic link. The experiment started with unperturbed straight walking to obtain normative data and continued with perturbed walking, where 4 different perturbation directions as shown in Fig. 2(a) (i.e. FW, BW, LEFT and RIGHT) with 5 repetitions of each were randomly applied to pelvis. The perturbations were triggered at left heel strike with the left foot switch signal approximately after 5 gait cycles. The perturbation amplitude was set to 15% of the body weight of each subject with perturbation duration of 150 ms. In order to keep the pelvis within the center of BARs workspace during unperturbed gait cycles, a monitor was mounted in front

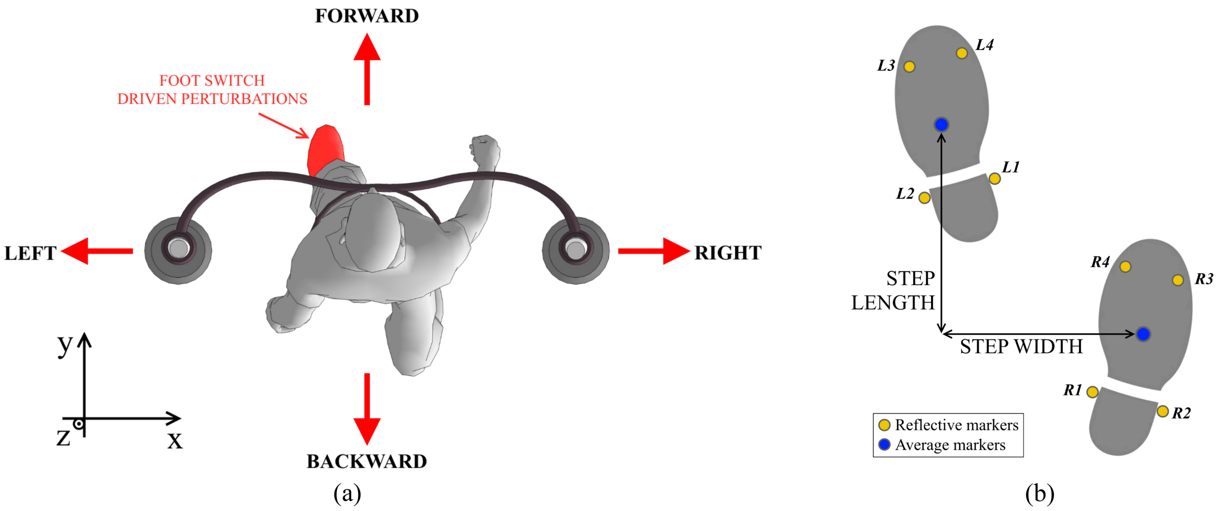

Fig. 2. (a) The directions of the perturbation forces during subject walking with attached pelvic link and foot switch as a trigger for perturbations; (b) step length and step width determination from reflective markers.

of the subject showing current pelvis position, which needed to be within a central BAR workspace. The walking speed was set to 0.85 m/s for all subjects and on both devices, where in BAR-OG the walking speed was triggered by the operator's joystick and hence the BAR-OG mobile platform dictated the subject's walking pace. After BAR-OG experiment, each subject was measured further with the BAR-TM with the same parameters and procedure.

2.3. Data analysis and statistics

The post processing of the motion data was done in Optitrack Motive software and further signal processing in MATLAB (Version R2015b, MathWorks, Inc.). In order to extract stepping responses determined as step length (SL), step width (SW) and step time (ST), we calculated the average position out of four marker positions for each lower extremity to get the foot center locations, which were used also to identify double stance gait subphases – Fig. 2(b). The SL and SW were extracted from the coordinates of the averaged markers at a time of double stance, while ST was calculated as an interval between two consecutive double stances. SL/SW/ST were normalized to the normative (unperturbed walking) data for each individual. For each perturbation direction a series of 6 alternating left and right SL/SW/ST were observed in order to get the whole stepping response on particular perturbation. All the perturbation directions were sorted, averaged for each individual and further used to obtain group averages and standard deviations. Stepping responses recorded with BAR-OG and BAR-TM were statistically evaluated using t-test (level of statistical significance: $p < 0.05$) and Pearson correlation coefficient.

3. Results

Figure 3 shows graphic illustration of stepping responses with footprints of the representative subject for the unperturbed (normative) walking and perturbed walking after applied perturbation directions with BAR-OG (darker footprints) and BAR-TM (lighter footprints). Stepping responses consists of consecutive steps labelled as $SL_{L1} \sim SL_{L3}$, $SL_{R1} \sim SL_{R3}$ as step lengths in AP distance and $SW_{L1} \sim SW_{L3}$,

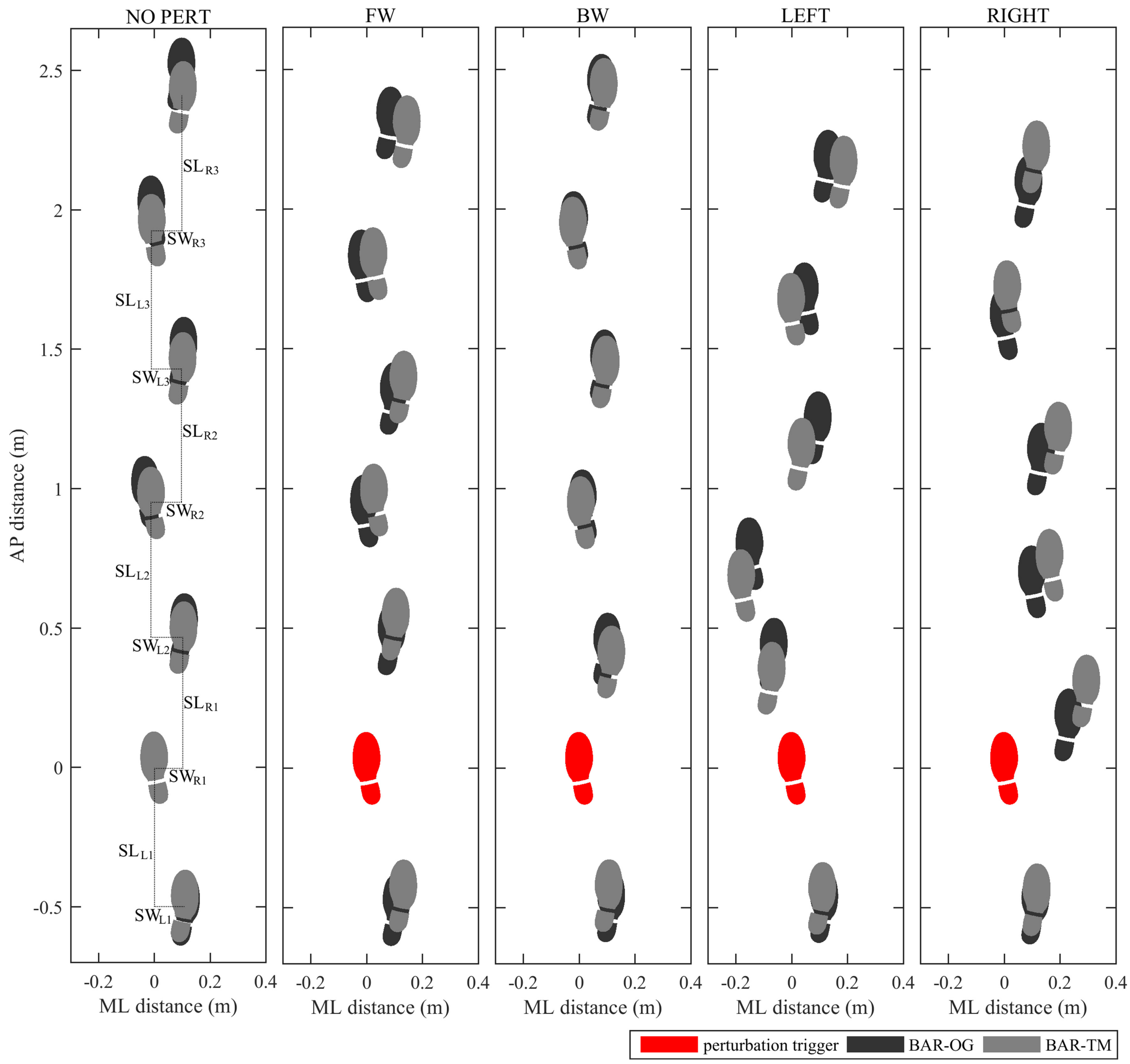

Fig. 3. Footprints of stepping responses of one representative subject following four different perturbation directions: forward, backward, left and right as well as unperturbed walking with BAR-OG (darker footprints) and BAR-TM (lighter footprints).

$SW_{R1} \sim SW_{R3}$ as step widths in ML distance. For adequate representation the stepping responses on perturbations are aligned with the first left footprint (red coloured) of the stepping sequence due to the perturbation command that started from this location onward. The group mean values with standard deviations of the normalized SL/SW/ST are shown in Fig. 4, where each stepping response on particular perturbation direction as well as the unperturbed walking consists of 6 consecutive left/right steps. Before group averaging the mean SL/SW/ST values were normalized separately for each individual to the mean SL/SW/ST values of his unperturbed walking in order to exclude the variability in gait cadence between subjects. Unperturbed stepping was very repeatable as indicated by small standard deviations and it was also uniform as indicated by equally high normalized mean values of SL/SW/ST. Here, the values of Pearson correlation coefficients are rather high ($\rho_{SL} = 0.7712$, $\rho_{SW} = 0.5137$, $\rho_{ST} = 0.8075$) with no significance ($p > 0.05$), but the t-test indicates no statistical significance ($p > 0.05$) between un-

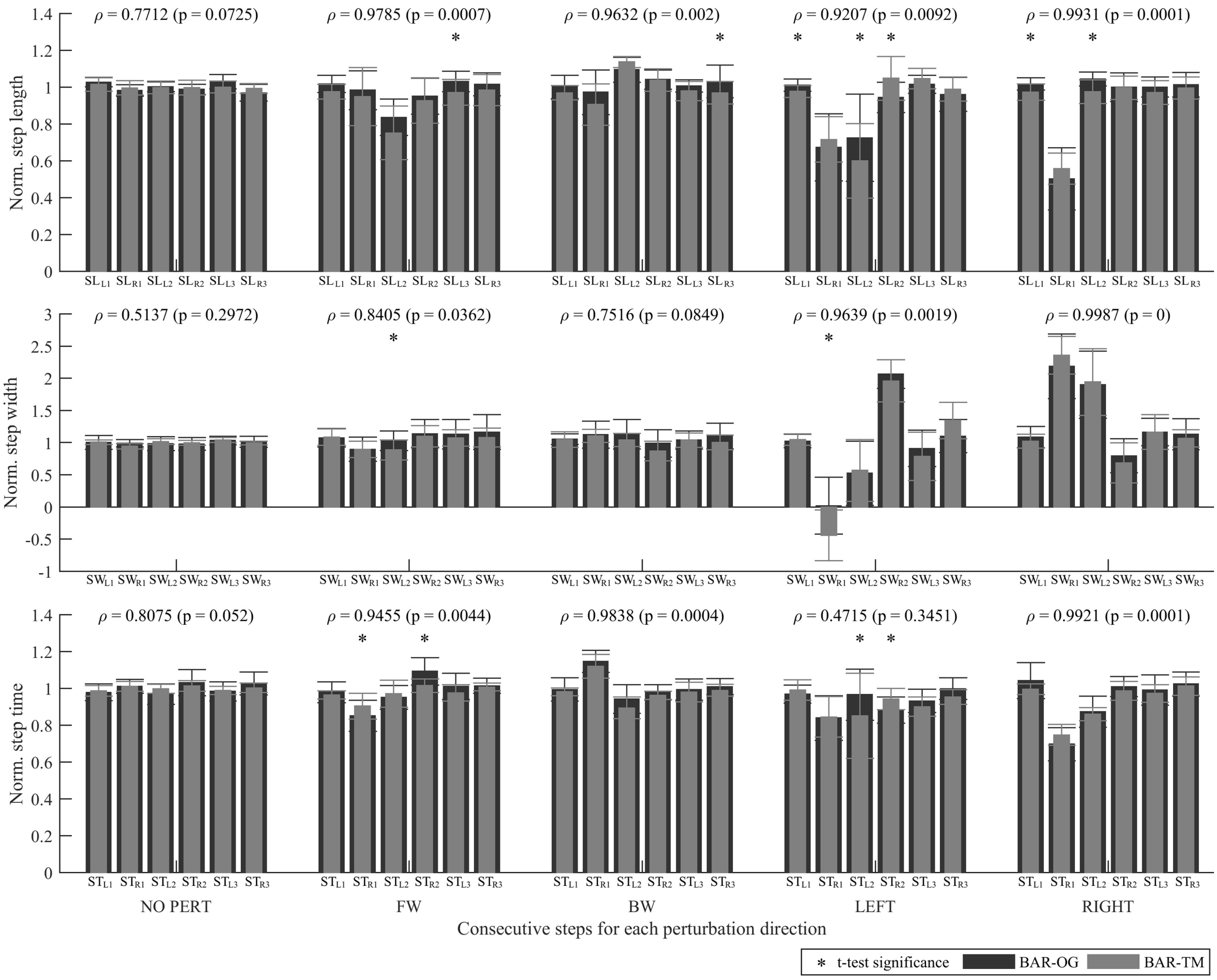

Fig. 4. Group average of normalized stepping responses (normalized step length, normalized step width and normalized step time) following perturbations during overground (darker bars) and treadmill walking (lighter bars).

perturbed walking with BAR-OG and BAR-TM when comparing each pair of stepping responses within a set of consecutive steps. In stepping responses of perturbed walking every first pair of steps (i.e. SL_{L1}, SW_{L1} and ST_{L1}) represent the unperturbed step before triggering the perturbation, while next 5 pairs of stepping responses are the consequence of the particular perturbation.

3.1. Perturbations in AP directions

When applying perturbation to the FW direction, the first step after perturbation commencement is significantly faster (ST_{R1}) and slightly narrower (SW_{R1}), while the SL_{R1} remains at the similar average height as the unperturbed SL_{L1} with a slightly increased standard deviation. The following step is significantly shorter (SL_{L2}) and slightly faster (ST_{L2}) than the previous step, while next 3 remaining steps are already close to the values of unperturbed walking condition with the exception of significantly increased step time ST_{R2} when walking in BAR-OG. Here, the Pearson correlation coefficient reveals significantly high correlations of stepping response sequence between walking in BAR-OG and walking in BAR-TM:

$\rho_{SL} = 0.9785$ ($p < 0.05$), $\rho_{SW} = 0.8405$ ($p < 0.05$) and $\rho_{ST} = 0.9455$ ($p < 0.05$), while t-test indicates significant differences at SL_{L3}, SW_{L2}, ST_{R1} and ST_{R2}. The perturbation to the BW direction cause significantly slowed-down step (ST_{R1}) immediately after perturbation commencement, slightly widened (SW_{R1}) and shortened step (SL_{R1}) on average with the increased standard deviation. The following step is significantly longer (SL_{L2}) and faster (ST_{L2}). Similarly as for the stepping response on FW perturbation direction, the last 3 remaining steps are close to the values of unperturbed walking condition. Here, the Pearson correlation coefficient reveals significantly high correlation of normalized SL and ST: $\rho_{SL} = 0.9632$ ($p < 0.05$), $\rho_{ST} = 0.9838$ ($p < 0.05$); while the coefficient of normalized SW is still relatively high $\rho_{SW} = 0.7516$ with no significance ($p = 0.0849$), which is due to the fact that SW changes very little following AP perturbations thus calculation of correlation coefficients in this case is not particularly relevant. The only significant difference the t-test indicates is at SL_{R3}. The perturbations in AP direction (FW, BW) require at least two steps that are needed to recover from perturbations.

3.2. Perturbations in ML directions

Perturbations in ML directions (LEFT, RIGHT) have a major impact on stepping responses. The perturbation to the LEFT direction caused an immediate cross-stepping response ($SW_{R1} < 0$) with significantly shortened (SL_{R1}) and slightly faster steps (ST_{R1}). The following step is also shorter (SL_{L2}) as compared to unperturbed step (SL_{L1}), while the step width becomes positive again ($SW_{L2} > 0$) and step time (ST_{L2}) changes only for BAR-OG environment. The width of the next step (SW_{R2}) is then significantly higher than previous one (SW_{L2}), which moves the subject back to the center position of walking in both environments. From here on, step lengths and step times are close to the values of unperturbed walking condition, while the step widths are still oscillating around its normative. The Pearson correlation coefficients reveal the normalized SL and SW as significantly correlated between OG and TM experimental conditions: $\rho_{SL} = 0.9207$ ($p < 0.05$), $\rho_{SW} = 0.9639$ ($p < 0.05$); while the coefficient of the normalized ST is fairly low ($\rho_{ST} = 0.4715$) with no significance ($p = 0.3451$). The t-test indicates significant differences at SL_{L1}, SL_{L2}, SL_{R2}, SW_{R2}, ST_{L2} and ST_{R2}. The perturbation to the RIGHT direction caused significantly shorter (SL_{R1}), wider (SW_{R1}) and faster steps (ST_{R1}) immediately after perturbation commencement. In the following two steps the SW oscillates (SW_{L2}, SW_{R2}) around the values of unperturbed walking, while ST gradually increased to the values of unperturbed walking (ST_{L2}, ST_{R2}). The SL already normalizes from the second step onward (i.e. $SL_{L2} \sim SL_{R3}$). The Pearson correlation coefficients reveal all three stepping responses (SL/SW/ST) as significantly correlated between OG and TM experimental conditions: $\rho_{SL} = 0.9931$ ($p < 0.05$), $\rho_{SW} = 0.9987$ ($p < 0.05$) and $\rho_{ST} = 0.9921$ ($p < 0.05$), while the t-test indicates SL_{L1} and SL_{L2} as significant differences. In the ML perturbation directions at least four steps are needed to recover normal walking after perturbation command.

In general, t-test indicated no statistical significance in 82% of all stepping response parameters following perturbations with BAR-OG compared to stepping response parameters following perturbations with BAR-TM. The overall average of Pearson correlation coefficient is 0.8597 ± 0.1711. The recorded stepping responses are consistent with the stepping responses of our previous study on BAR-OG, where postural responses to the perturbations applied to pelvis including equilibrium related variables are described in more detail [15].

4. Discussion

The scope of this study was to compare stepping responses elicited by perturbing pushes delivered to the pelvis during OG and TM walking.

4.1. Stepping responses in OG and TM experimental conditions

From the results related to unperturbed walking it can be observed that the relatively small standard deviations in the normalized SL/SW/ST defined consistent and uniform walking conditions in a group of healthy subjects. This can be observed in both BAR-OG as in BAR-TM experimental conditions. Here, we did not find any statistical difference in unperturbed consecutive steps between both devices. Pearson correlation coefficients were relatively low, which can be explained by the fact that SL/SW/ST parameters did not change much and stayed within a small range during unperturbed walking; thus calculation of correlation coefficients on data which do not change around its nominal value is not particularly relevant.

The results related to perturbed walking show that stepping responses following all four perturbation directions were highly correlated whether they were applied on a TM or OG. It is evident that the subjects consistently adjusted step lengths and step times when perturbation occurred in AP directions, while the step width was not changed much. Immediately after triggering FW perturbation first step reaction was reflected mostly in step time, where the subject needed to reduce the swing phase time in order to come to the double stance. The second step after triggering the FW perturbation is then reflected in significantly shorter step length. The opposite stepping reaction was observed after BW perturbation, where the swing phase of the first step was prolonged. In the following steps the subjects gradually caught up with the walking speed of the OG platform or the velocity of the TM. When perturbed in ML direction characteristic stepping responses are seen from our results. The perturbation to the left caused a cross-over step (negative step width) of the right leg in the first step after triggering the perturbation. This step was faster and much shorter than normal step. The following step was placed even more to the left to additionally decelerate movement in the frontal plane. Such stepping strategy was presented as the "outward strategy" [13]. In the case of perturbation to right the first two steps after perturbation were significantly shorter and faster in order to place the right foot to the side to make wider steps. Hof et al. referred such strategy as "inward strategy" [13].

4.2. Methodological considerations

Although both BAR devices are similar in its software and hardware we could notice some differences in balance responses in OG and TM experimental conditions, particularly following perturbations in the ML directions, which may be due to different mechanical structure of base frames of BAR-OG and BAR-TM devices. Base structure of mobile BAR-OG platform is more compliant thus attenuating the effect of perturbation pushes. BAR-TM on the other hand has a stationary platform, which makes it more rigid, and thus perturbation forces could be fully transferred from the mechanical construction through the pelvic link to subject's pelvis.

From the graphical illustration of stepping responses (shown in Fig. 3) it can be seen that the subjects walked with higher cadence and shorter steps in TM experimental conditions. Normalizing data of the perturbed stepping responses according to the SL/SW/ST parameters of unperturbed walking in each subject and on both platforms was therefore an important procedure that enabled us to explore correlation of stepping responses between OG and TM experimental conditions. It was also important that before conducting the experiment the participants walked for at least ten minutes on both BAR devices in order to get familiarized with the pelvic link, treadmill walking, walking within an equilibrium pelvis position via visual feedback and with the devices in general. Especially familiarization with the TM walking was needed to obtain steady state spatiotemporal parameters during unperturbed walking [27].

The results indicate high similarities between both experimental environments on a relatively small sample of subjects. However, further studies will take into account a larger number of subjects in order to verify this conclusions.

5. Conclusions

Studying balance on an instrumented treadmill has numerous advantages compared to overground walking especially from the rehabilitation perspective, where neurologically impaired subjects can easily be supervised by therapists. An adequate strategy of the stepping responses followed by the external perturbations is an important human function in order to maintain a stable balance during walking. This study showed high similarity of unperturbed and perturbed walking in a group of healthy subjects in both OG and TM experimental environments. Based on these results further treadmill-based perturbed walking studies can be done thus fully exploiting possibilities offered by instrumented treadmills enabling assessment of ground reactions forces.

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Conflict of interest

None to report.

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