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The biomechanical differences of wearing safety shoes compared with everyday shoes on dynamic balance when tripping over an obstacle

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ABSTRACT

Safety shoes are known to challenge dynamic balance, but the interaction between footwear and trips has not been thoroughly explored. This study investigated the biomechanical differences on dynamic balance during unexpected trip perturbations between safety shoes and everyday shoes. The vertical position of the whole-body center of mass (CoM) and the linear momentum of the swing leg from seven females and sixteen males were analyzed in five subsequent gait cycles. Additionally, the recovery strategies (i.e., the displacement of the foot after tripping) were classified. Wearing safety shoes, the linear momentum of the foot and whole leg increased, and the vertical position of the whole-body CoM was lower after the perturbation. Additionally, the recovery strategy when wearing safety shoes demonstrated a lower displacement of the foot. In conclusion, wearing safety shoes was found to have negative biomechanical effects when having to circumvent a trip, and this potentially increased the risk of falling.

1. Introduction

Occupational slips, trips, and falls are serious issues affecting safety and having major economic consequences (Chang et al., 2016; Orr et al., 2022). Trips due to unexpected perturbations challenge the dynamic balance during everyday activities (Chander et al., 2014, 2015, 2017). The trips typically occur in the mid-swing where the toe clearance is at its lowest (Begg et al., 2007). A protrusion as little as 5 mm can be enough to cause a trip (Begg et al., 2007; Chang et al., 2016), making trip situations very common. Further, the risk of falling after a trip is increased in occupational settings due to irregularities in flooring. This enhanced risk is most likely due to an increased momentum and quicker time sequences of fast walking (Chang et al., 2016). However, the enhanced risk may also be linked to the characteristics of safety shoes as underlined in a recent review (Orr et al., 2022).

In occupational settings, safety shoes are often mandatory to meet the workplace-specific safety regulations and serve as a common personal protective equipment (Orr et al., 2022). Safety shoes are often characterized by high mass, stiff toe cap, thick protective outer layer, thick protective midsole, anti-slip outer sole, electrical isolation, and an enclosing heel cap. All these factors are to prevent injuries of the feet (Chang et al., 2016; Dobson et al., 2017). However, they also result in decreased gait stability (Benjamin et al., 2017) and increased risk of falls after tripping (Chander et al., 2019). On the contrary, everyday shoes designed with a tight fit, lower mass, more flexible structure, lower heel drop, and thinner midsole and insole increase the gait stability and may improve the trip recovery and prevent workers from falling (Chander et al., 2019; Dobson et al., 2017; Orr et al., 2022).

Trip recovery depends on the ability to control the trunk movements and generate lower extremity muscular power. Here, the walking speed prior to the trip, the reaction time, the step length after the trip as well as the trip itself influence the ability to successfully recover from a trip (Chang et al., 2016). Recovery strategies after tripping take place in the swing phase of a gait cycle (Chang et al., 2016; Cordero et al., 2004; Eng et al., 1994; Forner Cordero et al., 2003, 2005; Shirota et al., 2014). The strategies are categorized as: (i) 'elevating strategy', i.e., elevating and placing the foot anteriorly to the perturbation (most frequent in the early swing phase), (ii) 'lowering strategy', i.e., lowering and placing the

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foot at or posteriorly to the perturbation (most frequent in the middle and late swing phase), and (iii) 'delayed strategy', i.e., related to a delay when the elevating strategy is changed to a lowering strategy. Still, little is known about postural recovery strategies in relation to safety footwear (Dobson et al., 2017), and especially in relation to trips (Chang et al., 2016). This has important practical implications as the risk of falling may be increased when wearing safety shoes (Chang et al., 2016; Chander et al., 2019; Orr et al., 2022).

This study aimed to fill this gap in knowledge by quantifying the biomechanical differences of wearing safety shoes and everyday shoes on dynamic balance after a perturbation during which a mechanical obstacle interrupts the forward motion of the swing foot. It was hypothesized that the vertical position of the whole-body center of mass (CoM) would fall lower after the perturbation and the linear momentum of the swing foot would be higher during and after the perturbation when wearing safety shoes compared with everyday shoes (Chang et al., 2016).

2. Methods

2.1. Inclusion and exclusion criteria of participants

Twenty-four asymptomatic participants took part in this randomized controlled crossover study. One dataset was corrupted and not used for analysis. Thus, data from 23 participants (seven females and sixteen males) were analyzed. The participants were 26.1 ± 4.2 years old, 1.77 ± 0.08 m height, weighed 79.5 ± 13.2 kg, and had a BMI of 25.2 ± 3.6 kg/m^2. Twenty participants were right leg dominant and three were left leg dominant. The inclusion criteria were shoe size 39, 42, 43, and 44 EUR (based on a pragmatic choice of available shoe sizes) and age 18–40 years old. Exclusion criteria were known neurological disorders or an injury in the lower extremities six months prior to the data collection. All participants were informed about the purpose of the study during the recruitment process and signed informed consent prior to the experimental protocol. The experiment was conducted in accordance with the North Denmark Region Committee on Health Research Ethics (LBK nr. 1083) and the Helsinki Declaration.

2.2. Experimental setup

The participants walked on a split belt treadmill (Split70/157/ASK, Woodway, Weil am Rhein, Germany) without handrails (dimensions: length: 1.70 m and width: 0.69 m) while wearing a slacked overhead safety harness to prevent potential falls.

The perturbation system consisted of a wooden board functioning as a mount board that elevated the system to the height of the treadmill (Fig. 1). A wooden beam (height: 2.7 cm, width: 4.2 cm, length: 120 cm) was placed between two fixed wooden blocks. The mount board raised the beam 0.4 cm above the treadmill to avoid vibrations causing an obstacle height of 3.1 cm (King et al., 2019; Schillings et al., 2000). The height was chosen in accordance with Austin et al. (1999) and was higher than the average minimum toe clearance reported (1.3 ± 0.4 cm) for asymptomatic adults (Begg et al., 2007). The blocks were fixed on the board allowing the structure to act as a prismatic joint providing linear sliding of the wooden beam. For safety reasons, a stop block was fixed onto the beam, making it unable to slide out onto the belt. Additionally, the beam was able to rotate in one direction around its vertical axis while resisting rotation the other way around. In this way, the beam could only obstruct the foot coming forward in the swing phase. When inducing a trip, a wire attached to the beam was manually pulled by the experimenter from behind the participant to drag the beam out in front of the swing leg to create a trip event. The perturbation system was placed laterally to the center of the treadmill where it was fixed firmly to the floor. A 23″ display was placed approximately 1.5 m anteriorly to the participant at a height of approximately 1.6 m to help the participant maintaining a stable anteroposterior position on the treadmill. The display showed a video of continuous straight walking and gave directional instructions in the top right corner (forward, backwards, left, and right) every 30 s. Additionally, a thin string was fixed anteriorly on the safety harness and onto a table in front of the treadmill to give tactile feedback. When the position on the treadmill was correct, the monitor would display 'fine'. Moreover, during walking a mirror was used to evaluate the position of the participants feet relative to the perturbation beam. The developed method was found successful for inducing trip perturbations in a prior pilot study (on average the perturbation was applied at 52.0 ± 5.6% into the swing phase).

Kinematic 3D data were collected using Xsens (Xsens Technologies,

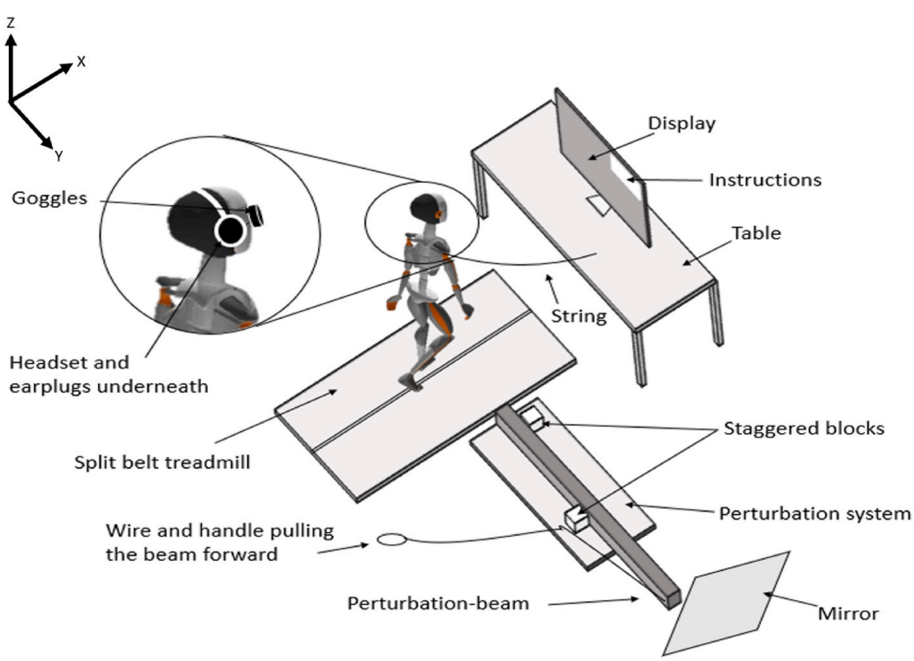

Fig. 1. Experimental setup.

B.V., Enschede, the Netherlands) and the supplied Xsens MVN software (Xsens MVN Analyze Pro, 2021.0.1). The Xsens system estimates full body kinematics using 17 IMUs, each measuring linear acceleration, angular velocity, and the magnetic field. Further, the system is reported reliable and valid (Al-Amri et al., 2018; Blair et al., 2018; J.-T. Zhang et al., 2013). Kinematic data were sampled at 240 Hz and data were reprocessed using the 'reprocess HD' option.

2.3. Experimental protocol

The participants wore a Xsens Link Lycra Suit. Anthropometric data (age, body mass, shoe size, dominant leg, height, shoulder height, shoulder width, elbow span, inter-wrist span, arm span, hip height, hip width, knee height, and ankle height) were measured and used for Xsens calibration ('npose + walking'). The dominant leg of the participants was determined by asking the participants which leg they preferred if kicking a ball. The participants were randomly divided into two groups: One group started wearing safety shoes (UVEX 1 s2 EN ISO 2345:2011, weight: 0.431, 0.491, 0.547, and 0.547 kg for sizes 39, 42, 43, and 44 EUR, respectively). The other group wore everyday shoes (VRS - Unisex Sneakers, weight: 0.168, 0.182, 0.193, and 0.201 kg for sizes 39, 42, 43, and 44 EUR, respectively) (Fig. 2). Both shoe types had a 3 cm sole height as recommended earlier (Dobson et al., 2017).

In agreement with van den Bogaart et al. (2020), the participants walked for approx. five minutes to get accustomed to the treadmill. The walking speed was set to 1.5 m/s (5.4 km/h) to mimic a work environment in which workers walk fast to meet production requirements (Chang et al., 2016). Subsequently, data were gathered in a total of eight trials, each containing a trip. Four trials were performed before the participants changed shoes to the type not yet worn. After this, four additional trials were performed. The participants were asked to regain normal gait after tripping without stopping or looking backward. Earplugs and a noise cancelling headset (Sony WH-1000XM4, Minato, Tokyo, Japan) playing music as loud as possibly comfortable were used to eliminate audio cues. Additionally, goggles with tape on the ipsilateral glass blocking part of the peripheral view (perturbation system) were used in agreement with Schillings et al. (2000). In every trial, the participants were blinded to the trips occurring at a random time between 180 and 480 s (random number generator). The experimental protocol took approximately 2 h.

2.4. Data analysis

Data were processed using MATLAB R2021b (The Mathworks inc, Natick, Massachusetts, U.S) and used for the data analysis. In total, five gait cycles were extracted; one before, one during, and three after the perturbed gait cycle to examine the recovery strategies in agreement with Forner Cordero et al. (2003).

2.4.1. Analysis of vertical position of center of mass and linear momentum

The term dynamic balance is often indicated by the margin of stability and the projection of the extrapolated CoM (Hof et al., 2005; Hof and Curtze, 2016; Tesio and Rota, 2019). Further, it is defined as the ability to control the vertical projection of the whole-body CoM relative to the base of support (Van den Bogaart et al., 2020). In the current study, the dynamic balance was not quantified based on the base of support and the margin of stability since the estimates of the base of support are unreliable when using Xsens (Guo and Xiong, 2017). Therefore, we extracted the vertical position of the whole-body CoM to obtain an estimate of the dynamic balance. The vertical position of the whole-body CoM and the linear momentum of the ipsilateral foot (from ankle to ball of the foot), shank, thigh, and whole leg (sum of linear momentum of foot, shank, and thigh) were calculated for five subsequent gait cycles. A gait cycle was defined by the initial contact of the right foot until the next initial contact of the right foot. The linear momentum of the segments was calculated as the product of the mass [kg] and velocity [m/s]. The mass of the foot, shank, and thigh was calculated by multiplying the proportion coefficients of the foot, shank, and thigh (i.e., 0.0145, 0.0465, and 0.1, respectively) by the body mass (Dempster 1955). The mass of the shoes was added to the mass of the foot. The velocity of each segment (v_s [m/s]) was calculated as the modulus of velocity measured in 3D (v_x, v_y, v_z).

Prior to the statistical analysis of the vertical position of the whole-body CoM and the linear momentum, each gait cycle was normalized to 100 data points by a linear interpolation using every other minimum in the vertical position of the whole-body CoM. Every other minimum in the vertical position of the whole-body CoM corresponded to the initial foot contact and the terminal swing phase of the ipsilateral foot (Orendurff et al., 2004). The average of the normalized data for each participant comprising four trials with safety shoes and everyday shoes respectively was used for statistics and plotted as five subsequent gait cycles.

2.4.2. Analysis of recovery strategies

The horizontal right toe displacement (HTD) and the peak vertical right toe elevation (VTE) were used to classify the recovery strategies. HTD [m] was calculated between the instant of the perturbation and 350 ms after the perturbation, using formula (1). VTE [m] was defined as the difference between the peak vertical position in a period of 350 ms after the perturbation and the vertical right toe position at the instant of the perturbation (Eng et al., 1994).

$$HTD = \sqrt{{F_{px\_350}}^2 + {F_{py\_350}}^2} - \sqrt{{F_{px\_0}}^2 + {F_{py\_0}}^2} \tag{1}$$

F_{px_350} [m] and F_{py_350} [m] are the right toe positions in the x and y direction 350 ms after the perturbation, and F_{px_0} [m] and F_{py_0} [m] are the right toe positions in the x and y directions at the instant of the perturbation.

Two thresholds were used to identify the recovery strategies: 1) The horizontal threshold (0.525 m) was the distance traveled by the perturbation at 350 ms caused by the movement of the treadmill. 2) The vertical threshold (0.031 m) was the height of the obstacle above the height of the right toe in the instant of the perturbation. If the right toe passed the horizontal threshold but not the vertical threshold, the strategy was classified as undefined in agreement with Shirota et al. (2014). The recovery strategies were defined as stated in Table 1. A descriptive analysis was used.

2.4.3. Analysis of percentage of perturbation, horizontal center of mass velocity, carry-over effect, and intra-subject variability

The instant of the perturbation was manually found for all trials by visual assessment of the frame-by-frame animations using Xsens MVN software and was based on the motion and horizontal velocity of the right foot as well as the bending of the metatarsal phalangeal joints. The percentage of the swing phase at which the perturbation occurred (PoP) was calculated using the foot contact data. The PoP was calculated by dividing the number of frames in the perturbed swing phase by the average number of frames in the three swing phases of the right leg prior to the perturbed swing phase multiplied by 100.

The mean horizontal velocity of the whole-body CoM ($v_{CoM,xy}$ [m/s]) was determined for both shoe conditions for the total length of the data by calculating the square root of the sum of the velocity of the whole-body CoM in the x and y direction. Further, the average of the first four trials was compared with the average of the last four trials to assess a potential carry-over effect. Additionally, trial 1, 2, 3, and 4 wearing safety shoes and everyday shoes respectively were compared to assess intra-subject variability.

2.5. Statistical analysis

Following an unpassed normality test, a 1D Statistical nonParametric Mapping (SnPM) two-tailed paired *t*-test was performed to analyze the

Fig. 2. The safety shoes (left side) and everyday shoes (right side) used in the study.

Table 1
Classification of recovery strategies.

	HTD <0.525 [m]	HTD >0.525 [m]
VTE >0.031 [m]	Delayed strategy	Elevating strategy
VTE <0.031 [m]	Lowering strategy	Undefined strategy

HTD: Horizontal right toe displacement. VTE: Peak vertical right toe elevation.

effect of the shoe type on the vertical position of the whole-body CoM, the linear momentum of the segments, and on the carry-over effect. Further, a 1D SnPM one-way repeated measure ANOVA was performed to test the intra-subject variability with a pairwise comparison post-hoc test using a 1D SnPM paired *t*-test of six pairs with a Bonferroni correction. Ten thousand permutations were used. SnPM scripts are available in the spm1d open-source package.[1] A thorough description of SPM and SnPM has been given by Pataky (2010) and Nichols and Holmes (2002), respectively. Statistical Package Social Science (IBM Corp. Released 2020, IBM SPSS Statistics for Windows, Version 27.0. Armonk, NY) was used for the PoP. Based on a Shapiro-Wilk test, a student's paired *t*-test was applied for the PoP. Data are presented as mean ± SD, and the alpha level was set to 0.05 and 0.008 for Bonferroni correction.

3. Results

3.1. *Vertical center of mass and linear momentum comparing the shoe types during trips*

Before the perturbation, the vertical position of the whole-body CoM was significantly lower wearing safety shoes compared with everyday shoes ranging from 51 to 61% of gait cycle 1 with a peak difference of 0.4 cm ($P = 0.009$; Fig. 3). The vertical position of the whole-body CoM was significantly lower ranging from 84% of gait cycle 2–9% of gait cycle 3 when wearing safety shoes compared with everyday shoes with a peak difference of 0.6 cm ($P < 0.001$). The vertical position of the whole-body CoM was significantly lower ranging from 2 to 8% and 88–93% of gait cycle 5 when wearing safety shoes compared with everyday shoes with a difference of up to 0.3 cm ($P = 0.001$).

The linear momentum of the foot, shank, thigh, and whole leg increased and declined later when wearing safety shoes compared with

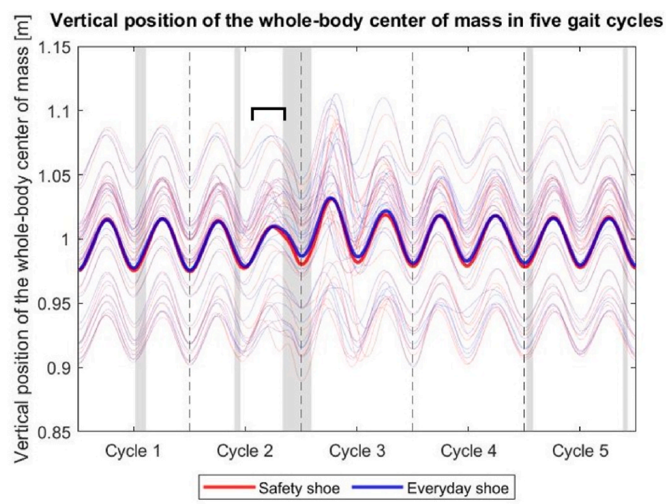

Fig. 3. Results of the Statistical nonParametric Mapping of the normalized vertical position of the whole-body center of mass over five subsequent gait cycles wearing safety shoes and everyday shoes. The perturbation occurred approximately at the second peak of gait cycle 2 as indicated by the bold square bracket (NB: The area represents the variation in recovery strategies of each participant). Dotted lines represent the beginning and end of the five gait cycles. Bold blue and bold red lines represent the average for each shoe condition. Thin blue and thin red lines represent the average of each participant across four trials wearing safety shoes and everyday shoes. Light grey shaded areas represent supra-clusters with a significant difference ($P < 0.05$) between the two shoe conditions. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

everyday shoes resulting in many supra-clusters in gait cycle 1 (Fig. 4). A significantly higher linear momentum of the right foot was found from 69% in gait cycle 1–16% in gait cycle 2 when wearing safety shoes compared with everyday shoes with a peak difference of 3.6 N s ($P < 0.001$). In the perturbated gait cycle (gait cycle 2) the linear momentum of the foot and whole leg was significant higher wearing safety shoes compared with everyday shoes, with the foot showing a significant difference from 57% to 71% ($P < 0.001$) and from 81% to 91% ($P = 0.001$) and the whole leg from 58% to 71% ($P < 0.001$) and from 87% to 94% ($P = 0.003$). In the subsequent recovery gait cycles, the linear moment of the right foot showed a significantly higher linear

[1] https://Spm1d.org.

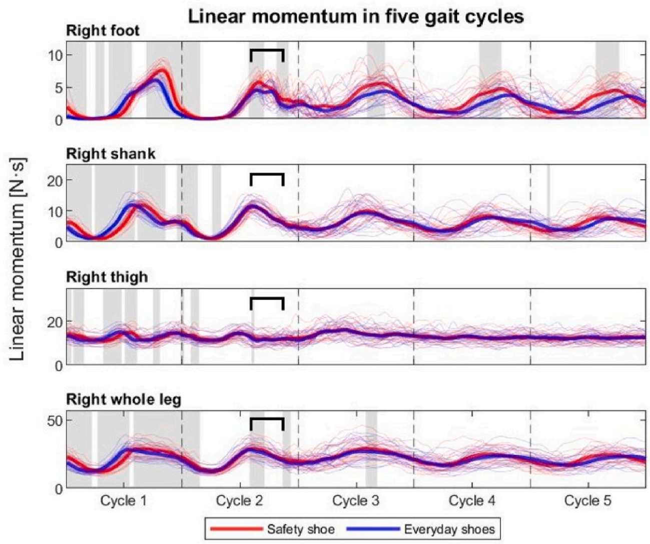

Fig. 4. Results of the Statistical nonParametric Mapping of the normalized linear momentum in the right foot, shank, thigh, and whole leg over five subsequent gait cycles wearing safety shoes and everyday shoes. The perturbation occurred approximately at the peak of the linear momentum of the foot in gait cycle 2 as indicated by the bold square bracket (NB: The area represents the variation in recovery strategies of each participant). Dotted lines represent the beginning and end of the five gait cycles. Bold blue and bold red lines represent the average for each shoe condition. Thin blue and thin red lines represent the average of each participant across four trials wearing safety shoes and everyday shoes. Light grey shaded areas represent supra-clusters with a significant difference ($P < 0.05$) between the two shoe conditions. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

momentum from approximately 57%–76% in gait cycle 3, 4, and 5 wearing safety shoes compared with everyday shoes ($P < 0.001$). The linear momentum of the right whole leg showed a significantly higher linear momentum ranging from 58% to 68% in gait cycle 3 when wearing safety shoes compared with wearing everyday shoes, though the variance of the data increased after the perturbation.

3.2. *Recovery strategies comparing the shoe types during trips*

Based on descriptive statistics, the elevating strategy was less frequent when wearing safety shoes compared with everyday shoes but was favored in both shoe conditions (Fig. 5 and Table 2). The average horizontal displacement of the right toe was 0.57 ± 0.20 m wearing safety shoes and 0.62 ± 0.18 m wearing everyday shoes. The average peak vertical elevation of the right toe was 0.06 ± 0.03 m wearing safety shoes and 0.08 ± 0.05 m wearing everyday shoes.

3.3. *Percentage of perturbation, horizontal center of mass velocity, carry-over effects, and intra-subject variability*

The perturbation occurred significantly later when wearing safety shoes compared with everyday shoes; 53.5 ± 2.9% (ranging from 44.0% to 60.4%) and 52.0 ± 3.5% (ranging from 46.2% to 60.9%) into the swing phase, respectively ($P = 0.019$). The mean horizontal velocity of the whole-body CoM wearing safety shoes and everyday shoes was 1.55 ± 0.07 m/s. No carry-over effect was found between the first four and last four trials. A significant difference was detected in the intra-subject variability of the vertical position of the whole-body CoM ranging from 86 to 87% of gait cycle 4 ($P = 0.026$) and from 1 to 18% of gait cycle 5 ($P = 0.022$) when wearing safety shoes. When wearing everyday shoes, the significant difference ranged from 89% of gait cycle 4–6% of gait cycle 5 ($P = 0.023$). The pairwise post-hoc comparison test showed that the

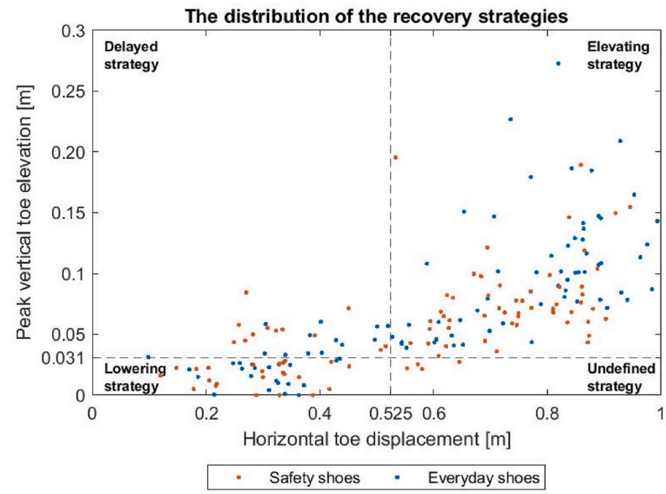

Fig. 5. Horizontal displacement of the right toe and peak vertical right toe elevation after the perturbation. Each dot represents a trial wearing safety shoes (red dots) and everyday shoes (blue dots). Dotted lines represent the horizontal and vertical threshold used to identify the recovery strategies after trips. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 2
The distribution of recovery strategies after trips.

	Elevating[%]	Lowering[%]	Delayed[%]	Undefined[%]
Safety shoes	56.5	26.1	13.0	4.3
Everyday shoes	63.0	22.8	14.1	0.0

vertical position of the whole-body CoM in trial 1 was significantly higher than in trial 3 ranging from 15 to 17% of gait cycle 5 ($P = 0.004$) when wearing safety shoes. The results of the carry-over effect and the intra-subject variability are shown in supplementary material S1 and S2.

4. Discussion

This randomized controlled crossover study was the first to investigate the biomechanical differences of wearing safety shoes and everyday shoes on the dynamic balance during trips elicited by a mechanical obstacle interrupting the forward motion of the swing foot. In line with our hypothesis, the whole-body CoM was significantly lower after the perturbation when wearing safety shoes compared with wearing everyday shoes. Further, the linear momentum of the foot and whole leg was significantly higher before, during, and after the perturbation when wearing safety shoes compared with wearing everyday shoes. Based on descriptive statistics, the elevating strategy was less frequent when wearing safety shoes compared with everyday shoes but was favored in both shoe conditions.

4.1. *A new method of inducing a trip*

Studies investigating trips should control the timing of the perturbation and elicit a trip in a realistic manner, thus minimizing the anticipatory responses. However, the setup should also be reliable to introduce the perturbations repeatedly (King et al., 2019). Generally, a trip is provoked in a realistic manner if the perturbation is applied to the swing leg during its forward motion by a mechanical obstacle on a treadmill or a walkway (King et al., 2019). Therefore, a mechanical obstacle was chosen. Further, the choice of a treadmill was important as walkways are often limited in length and constructed in a way the subjects must control their gait velocity and foot placement for the timing of the perturbation. A treadmill also enables participants to walk for a longer time before receiving the perturbation. Thereby the anticipatory response is reduced allowing for data capture at three steps or more after the perturbation. At the same time the procedure is reliable even though it slightly affects the stride length and stride rate (Forner Cordero et al., 2003; King et al., 2019; Oliveira et al., 2016).

King et al. (2019) and Schillings et al. (2000) provoked a trip by placing obstacles on the treadmill from the front at approx. the same horizontal velocity as the treadmill. In our study, the perturbation was applied from the side causing the swing foot to collide at a lower velocity relative to the mechanical obstacle. No vibrations were induced to the treadmill as the perturbation system did not touch the treadmill, resulting in reduced anticipative responses. Anticipatory responses were also reduced using a noise cancelling headset, music, earplugs, a video of continuous straight walking, and a randomized perturbation protocol making the prediction of the instant of the perturbation difficult (Schillings et al., 2000).

The timing of the perturbation was controlled manually using a mirror, a string, and directional instructions on a display. This was timed successfully as the PoP was at $53.5 \pm 2.9\%$ and $52.0 \pm 3.5\%$ of the swing phase when wearing safety shoes and everyday shoes, respectively. This suggests that the method was reliable. As the difference in PoP was small and with similar range, it can be seen as neglectable and making the shoe conditions comparable. This would not be the case with a larger difference in PoP as this would change the movement of the whole-body CoM (Eng et al., 1994). The intra-subject variability test showed that the vertical position of the whole-body CoM was significantly higher in trial 1 compared with trial 3 when wearing safety shoes. This difference was not seen in trial 4 and was only relevant for 2% of gait cycle 5. Moreover, the standardization of the protocol did not result in a carry-over effect confirming that the trip recovery depended on shoe wear. This enabling the results to assess the biomechanical effects of safety shoes.

4.2. Vertical center of mass and linear momentum

After the time normalization, there was an offset in the linear momentum of the right foot with respect to the vertical position of the whole-body CoM showing increased and peak linear momentum occurring later in gait cycle 1 when wearing safety shoes compared with wearing everyday shoes (Fig. 4). This underlines an altered gait strategy when wearing safety shoes as reported previously (Benjamin et al., 2017; Chang et al., 2016; Dobson et al., 2017). However, the dynamic balance was not notably affected after the perturbation as the peak difference in vertical position of the whole-body CoM was only 0.6 cm lower when wearing safety shoes compared with wearing everyday shoes (Fig. 3). The difference of 0.6 cm could be due to the heavier shoe and higher linear momentum in the foot and whole leg during and after the perturbation when wearing safety shoes compared with everyday shoes. Though, no participants fell after the trip as the vertical position of the whole-body CoM had been stabilized in gait cycle 5. However, a faster walking speed would potentially increase the fall risk while wearing safety shoes (Chang et al., 2016). Further, the literature suggests that heavier footwear increases the risk of falling after tripping (Dobson et al., 2017; Orr et al., 2022) as the heavier footwear decreases the toe clearance (Chiou et al., 2012). Combined with an increased occupational load and occasionally wearing heavy clothes, this could further increase the risk of falling (Park et al., 2010). Additionally, if trips occur while carrying a heavy load or dual tasking (e.g., walking and texting simultaneously), the postural corrections of the arms, shoulders, and upper body are modified. This inhibits the ability to control the whole-body CoM and thereby increases the risk of falling (Chang et al., 2016; Crowley et al., 2019). Of note, other factors like tiredness and working conditions also increase the risk of falling (Chang et al., 2016) highlighting the importance of trip-safe footwear. Therefore, several studies recommend the use of minimalistic footwear design (i.e., tight fit, low mass, flexible structure, low heel drop and thin midsole and insole) when designing safety shoes. In addition to these factors, the design should meet the safety regulations (Chander et al., 2019; Chang et al., 2016; Orr et al., 2022). However, the young and healthy participants in this study were able to generate enough muscle power and change the placement of the feet in a rapid manner. Thus, they recovered successfully from the trips even if higher linear momentum in the foot and leg were seen in gait cycle 2 and 3 when wearing safety shoes compared with wearing everyday shoes. Even though no falls occurred, our biomechanical analyses confirmed that the dynamic balance was increasingly affected when wearing safety shoes compared with everyday shoes during and after unexpected trips.

4.3. Recovery strategies

The elevating strategy was less frequent when wearing safety shoes compared with everyday shoes; 56.5 vs. 63%, respectively. The difference of 6.5% was most likely due to the heavier safety shoes which increased the required muscular power to perform especially the elevating strategy compared with the lowering strategy (Forner Cordero et al., 2005). However, the elevating strategy was predominant in both shoe conditions indicating that the young and asymptomatic participants were able to elevate their whole-body CoM (Fig. 3) due to a better ability to generate high muscular power. The use of the elevating strategy may also explain the difference in the vertical position of the whole-body CoM after the instant of the perturbation as the whole-body CoM was lower wearing safety shoes compared with everyday shoes. This strategy gave the participants more time to adjust their swing leg after the perturbation and adjust the base of support (Eng et al., 1994). In gait, the initial recovery strategy depends on the feedforward control by which a pre-planned recovery movement is used (Ghez et al., 1991; S. Zhang and Li, 2013). Hence, closed-loop feedback can explain the distribution of recovery strategies, especially the delayed strategy.

The high frequency of the elevating strategy was contradictory to previous findings reporting the lowering and the delayed strategy as the most common in the mid-swing (Eng et al., 1994; Forner Cordero et al., 2003, 2005; Shirota et al., 2014). To identify the recovery strategy, a fixed time point (350 ms) was used for the horizontal threshold and a time frame (up to 350 ms) for the vertical threshold, considering the large time variability (range 200–500 ms) for ground contact after the perturbation. This also applied to the short time to ground contact in the lowering strategy and long time to ground contact in the elevating strategy (Eng et al., 1994). Moreover, the difference in frequency of the elevating strategy could also be due to variations in the used perturbation methods. Several perturbation methods have been applied in the literature such as trip-like responses by rope pulling (Forner Cordero et al., 2003, 2005; Shirota et al., 2014) and obstacles on the treadmill and walkways at various heights (4.5 cm (Schillings et al., 2000), 8.0 cm (Eng et al., 1994), and 7.5 cm (King et al., 2019)). All of these are higher than the mechanical obstacle used in the current study and often too high to reflect an obstacle at the workplace (Chang et al., 2016). The height of the obstacle in this study was chosen in line with previous studies (Austin et al., 1999; Begg et al., 2007; Winter, 1992). In summary, the high frequency of the elevating strategy could indicate that the classification of recovery strategies is not only affected by the timing of the perturbation in the swing phase and the shoe type, but also by the obstacle height and even the perturbation velocity relative to the participant. The current study underlines the need for a consensus regarding the classification of recovery strategies.

4.4. Limitations of the study

Young females and males took part in this study. However, obese, or older participants may have had more difficulties recovering their gait pattern after a trip (Chang et al., 2016). Only one safety and one everyday shoe with common characteristics for each shoe type were tested, meaning the reported biomechanical adaptations may not be generalized to other shoes with other design characteristics (i.e., mass, high shaft, and protective style) as the biomechanical adaptions can differ as an effect of design characteristics (Dobson et al., 2017; Orr et al., 2022). However, the result is expected to be the same wearing other shoes sharing some or all the design characteristics of the shoes used in the current study. Future studies investigating trip recovery with other populations and different shoe types are warranted. Finally, a sample size estimation was not conducted in this explorative study in which a primary outcome measure and a corresponding functional meaningful difference were not a priori defined.

4.5. Conclusion

This study investigated the biomechanical differences on dynamic balance during unexpected trip perturbations between safety shoes and everyday shoes. When wearing safety shoes, the vertical position of the whole-body CoM was significantly lower after the perturbation compared with wearing everyday shoes. The linear momentum of the foot and whole leg was significantly higher before, during, and after the perturbation when wearing safety shoes compared with wearing everyday shoes. Based on descriptive statistics, the elevating strategy was less frequent when wearing safety shoes compared with everyday shoes but was favored in both shoe conditions. Overall, wearing safety shoes was found to have a negative effect when having to circumvent a trip, and potentially this increased the risk of falling.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apergo.2023.104040.

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