# Stability and Manoeuvrability Interactions During Human Walking Depend on the Manoeuvre Direction

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## Abstract

The interplay between stability and manoeuvrability is fundamental for human walking. Previous research finds conflicting perspectives on how these attributes interact – mechanisms for stable walking can either facilitate or impede manoeuvrability. We postulate that these views can be explained by considering manoeuvre direction. We hypothesize that adopting gait patterns that increase lateral stability will impede laterally-directed manoeuvres but not medially-directed manoeuvres due to body positioning strategies that resist lateral movements but aid in the ability to actively generate medially-directed external moments. Twenty-four participants performed many repetitions of a discrete stepping task involving mid-trial reactive manoeuvres in both a Baseline (no external perturbations) and Complex (random perturbations applied to their pelvis) environment. We found that in the Complex environment all participants increased their lateral margin of stability when compared to the Baseline environment. This resulted in an increase in manoeuvre reaction time and foot placement error for laterally-directed manoeuvres but not for medially-directed manoeuvres in the Complex environment when compared to the Baseline environment. These results support our hypothesis and provide the novel interpretation that the stability-manoeuvrability trade-off during human walking depends on manoeuvre direction.

## 1.0 Introduction

From aircrafts (1,2) to robotics (1,3) to animals (4–7), substantial research has studied how body shape influences movement stability and manoeuvrability. A major finding is that characteristics that improve stability limit manoeuvrability and vice versa. To understand this relationship, it is important to recognize that some of these characteristics are flexible. Animals, for example, have the capacity to change their body dynamics and generate external forces that may modify the interactions between stability and manoeuvrability on an ongoing basis during movement. In the current study, we find the relationship between stability and manoeuvrability during human walking depends on manoeuvre direction, indicating that characteristics that improve stability can either facilitate or impede manoeuvrability.

Real-world situations, such as walking quickly through a moving crowd of people, are challenging because they require gait patterns that are both stable (able to resist and recover from perturbations) and manoeuvrable (able to rapidly and precisely change walking direction). Prior research has found conflicting perspectives on the mechanisms people use to navigate these complex walking environments (situations that challenge both stability and manoeuvrability). Some research has found that gait patterns that improve stability limit manoeuvrability (8), while other research suggests the opposite, gait patterns that improve stability facilitate manoeuvrability (9). Additionally, while prior research has found that stability in the form of external support facilitates accuracy in single-step tasks, the relationship between adapting stable gait patterns and manoeuvre accuracy has not been well explored (10). Thus, the effect of adopting stable gait patterns on the capacity to manoeuvre is not well understood. We believe that these conflicting perspectives can be resolved by accounting for the state of the body and direction of the manoeuvre when the manoeuvre is initiated. For example, consider the first half of the stance phase when the whole-body centre of mass (COM) has a lateral velocity directed outwards towards the stance limb. During this period, frontal-plane stability can be enhanced by taking wider steps (11). However, this body

position will have different effects on manoeuvres depending on the manoeuvre direction. A wide step will resist volitional attempts to initiate a lateral manoeuvre (COM moves towards the stance limb) but assist with the initiation of medial manoeuvres (COM moves away from the stance limb). Thus, the effect of stable walking patterns on the capacity to manoeuvre may change depending on the period of the gait cycle and the manoeuvre direction.

A simple inverted pendulum model of walking provides further insight into the interaction between frontal-plane stability and manoeuvrability. Based on this model, a lateral margin of stability (MOS) can be calculated as the distance between the extrapolated centre of mass (XCOM) – a metric accounting for both COM position and velocity – and the base of support (BOS) (12). During walking, the impulse needed to move the XCOM beyond the BOS is proportional to the MOS (12). When the XCOM is positioned within the BOS (a positive MOS), gravity will accelerate the COM medially. When the XCOM position exceeds the BOS, the system is no longer passively stable as gravity will accelerate the COM laterally and will require a corrective action (such as a cross-over step) to recapture the COM within the BOS and ultimately remain upright. Many studies have observed that people will adapt gait patterns that increase their lateral MOS in response to ongoing or potential threats to their frontal plane stability during walking (13,14). These findings suggest that modulation of lateral MOS during walking is a common strategy people use to maintain gait stability in complex environments.

The inverted pendulum model can explain the stability-manoeuvrability trade-off that has been observed during walking. Adopting body positioning strategies to increase the lateral MOS, such as taking wider steps or reducing the COM velocity directed toward the BOS, should increase the body's mechanical resistance to frontal plane perturbations. However, these stable locomotion patterns can limit manoeuvrability because increasing the lateral MOS will also indiscriminately resist any self-imposed forces intended to change the direction of one's trajectory (15). As the lateral MOS increases, larger

impulses are required to overcome the body's resistance to lateral movements (16,17). This resistance may increase the time required to initiate a manoeuvre. Therefore, during periods of single limb support, increasing the lateral MOS should increase stability (resistance to lateral-directed perturbations) and decrease the capacity to manoeuvre quickly and accurately in the direction of the BOS.

Alternatively, this same body position during walking may be beneficial for initiating a medially-directed manoeuvre (COM movement away from stance limb). This is supported by the observation that people can select strategies that simultaneously increase both stability and manoeuvrability (9). For example, walking with wider steps will increase the gravitational moment acting about the ankle joint to accelerate the COM medially and position the stance limb in a desirable location to generate medially-directed ground reaction forces. Specifically, a wider step increases the splay angle (angle describing the spread of the limb relative to midline of the body) of the stance limb in the frontal plane that will enable the relatively large hip, knee, and ankle extensor muscle groups to contribute to the generation of medially-directed ground reactions forces (18). In addition, reducing the COM velocity directed toward the stance limb, which would also increase the lateral MOS, would aid in initiating medially-directed manoeuvres by reducing the medially-directed ground reaction force impulse needed to overcome the lateral momentum of the COM. Thus, increasing the lateral MOS during walking may reduce lateral manoeuvrability and improve medial manoeuvrability.

The objective of this study was to quantify the impact of adapting stable gait patterns on manoeuvrability. We had people walk in a complex environment that included external perturbations that could disrupt frontal plane stability and required frequent laterally- or medially-directed manoeuvres. The goal of the external perturbations was to induce people to adapt gait patterns that would increase their frontal plane stability. To study the interactions between lateral stability and manoeuvrability we compared how quickly and accurately people performed walking manoeuvres in the complex environment to similar manoeuvres

performed in a baseline environment with no external perturbations. We hypothesized that in the complex environment people would increase their lateral MOS stability which would increase manoeuvre reaction time and decrease manoeuvre accuracy for laterally-directed manoeuvres but not for medially-directed manoeuvres when compared to similar manoeuvres performed in the baseline environment.

## 2.0 Methods

### 2.1 Participants

Twenty-four adults (25.6 ± 2.9 years, height 1.7 ± 0.1 m, weight 72.8 ± 14.2 kg, 14 males, mean ± standard deviation) participated. The Northwestern Institutional Review Board (IRB) approved the protocol, and all participants gave written informed consent. Participants did not have any known musculoskeletal or cardiovascular injuries/impairments affecting their gait or balance. All participants self-reported the ability to walk continuously for 30 minutes without experiencing fatigue, health risks, or other limitations. Twenty-one participants self-reported right-foot dominance.

### 2.2 Experimental Setup

Participants performed a series of discrete stepping trials that involved stepping quickly from a start target to an end target. The targets were projected on the floor using a short-throw projector (Hitachi America, ltd.). Each target consisted of a pair of parallel ellipses, one for each foot, with 0.3 m major and 0.15 m minor axes and no gaps between them (Fig. 1A). To mitigate the risk of falls, participants wore a trunk harness attached to an overhead safety support trolly that allowed free fore-aft motion. A string potentiometer was attached to the front of the harness to monitor participants' real-time forward walking velocity. An audible "beep" cued the start and end of each trial. To encourage similar walking speeds across participants (1.0-1.3 m/s), peak forward velocity was displayed on a monitor positioned in front of the walking path during each practice trial.

The end target location was located 1.5 leg lengths in front of the start target at the start of all trials. For half of the trials, the end target remained directly in front of the start target (Straight trials). For the other half of trials, the end target shifted mid-trial 8° laterally (Target Shift trials; Fig. 1B). Participants were randomly assigned to either a Lateral or Medial manoeuvre group that would experience target shifts exclusively to the right (12 participants) or left (12 participants), respectively, for the entire experiment. During Target Shift trials, the target location would jump to the shifted location when the participant's forward walking velocity exceeded a threshold of 0.4 m/s. Thus, participants did not learn of the end target location for each trial until they began walking forward ("go before you know"). This setup encouraged participants to react to the target movement rather than try to pre-plan movement trajectories for each trial.

Forces were applied medio-laterally to the participants' pelvis using a cable-driven robot (Fig. 1A). The robot consisted of two independent series elastic actuators (linear motor and spring) that transmitted bilateral forces through a cable transmission system to a snug pelvic harness worn by the participant (19). Depending on the trial, a custom-written LabVIEW VI (National Instruments) code commanded the robot to apply one of two patterns of forces to the participant (Fig. 1C):

Null: Zero net medio-lateral force applied during the stepping trial

Random: A series of square-wave impulse forces. Each impulse force had a randomly generated direction (left or right), magnitude (75-90 N), and duration (300-500 ms). The total impulses applied for each trial were randomized to be either 1 or 2. Forces were checked during pilot testing to ensure the vector sum of all total forces applied during a session was 0 N.

We collected motion capture data to estimate the whole-body centre-of-mass (COM) trajectory and measure foot placement location for each trial. We collected kinematic 3D marker data using a 12-camera motion capture system (Qualisys, Gothenburg Sweden) sampling at 100 Hz. We placed 15 passive

reflective markers on the pelvis and bilaterally on the greater trochanter, lateral malleolus, calcaneus, and the 2nd, 3rd, and 5th metatarsals.

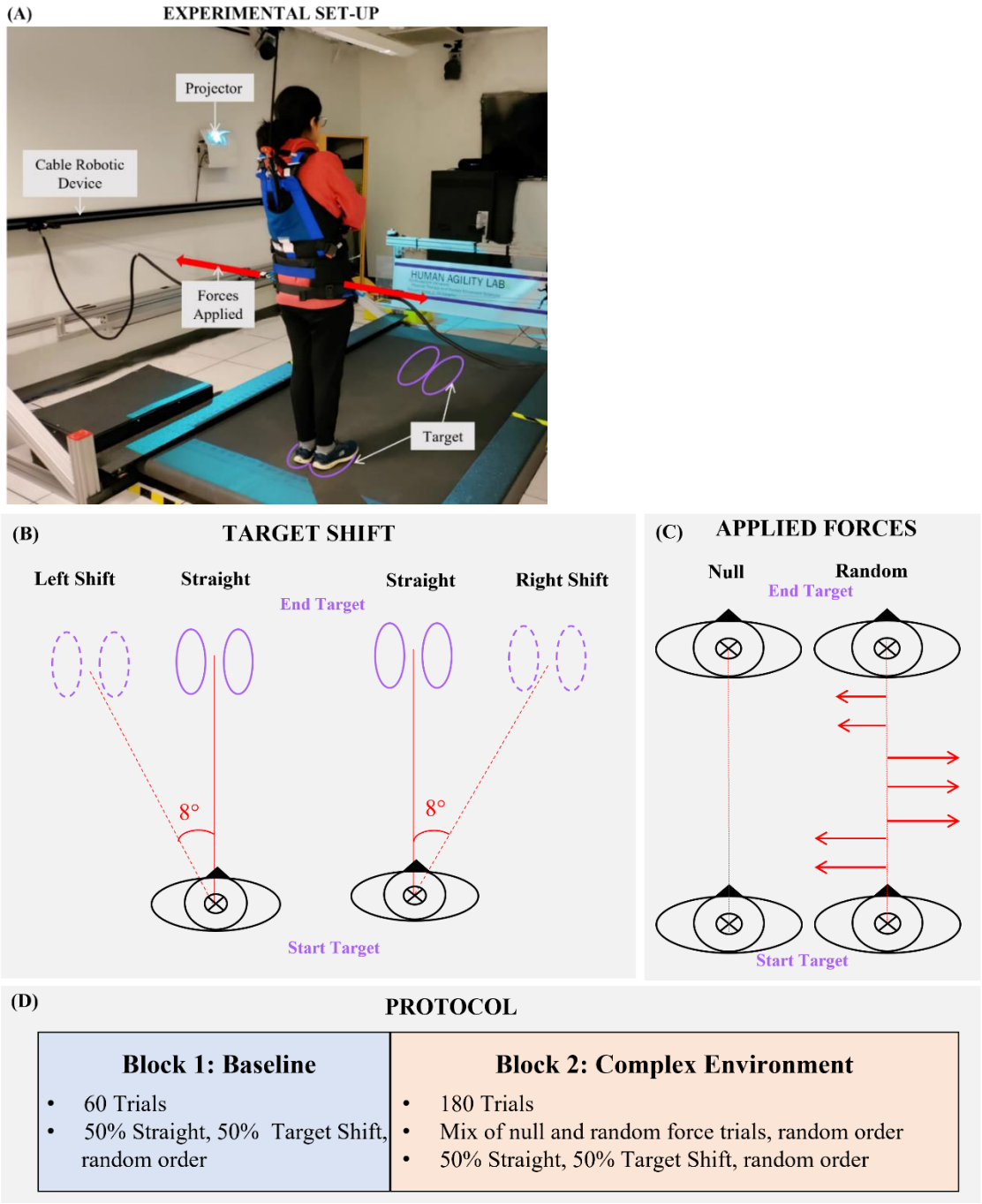


**Figure 1.** (A) Experimental Set-Up: Participants performed a series of stepping trials. Start and end targets consisted of a pair of parallel ellipses projected using a short-throw projector. The end target was at a distance of 1.5x their leg length. Medio-lateral forces were applied through a pelvic harness worn by the participant using a cable-driven robot on select trials. (B) Target Shift: Representation of a left and right target shift. On select trials, the target was instantaneously moved after the participant began forward walking. (C) Applied Forces: Types of forces applied by the cable robot during select trials (D) Protocol: Participants performed 240 trials, split into two blocks – Baseline and Complex environment.

## 2.3 Protocol

Participants first performed eight practice trials. These provided experience stepping to end targets that were straight ahead or shifted laterally during the trial. They also provided practice of a mix of Null and Random force trials.

Participants then performed a total of 240 discrete stepping trials, consisting of a block of 60 Baseline trials (Null forces every trial), followed by a block of 180 trials in a Complex environment (a mix of 120 Random and 60 Null force trials that varied trial-to-trial) (Fig 1D.). These Null trials were randomly embedded once every three trials (one Null and two Random force trials). The end target shifted during half of the trials in each block (30 in Baseline, 90 in the Complex environment). The order of Straight and Target Shift trials was randomized.

For each trial, participants always stepped first with their right leg. Participants were not informed if they would experience Null or Random forces each trial or whether the target would shift location. Participants were instructed to start the trial when they heard a start “beep” and to step to the target as accurately as possible. The trial concluded when the participant had taken 3 steps to the target (the first right step, then a left step that would ideally land in the left end target, and finally another right step that would ideally land in the right end target). A stop “beep” indicated the trial was complete. No forces were applied as participants stepped backwards to reset to the start target location for the next trial. To minimize the possible effect of arm swing on stability and manoeuvrability, participants crossed their arms across their chest during the stepping trials. Participants were instructed to walk in the manner and speed that they felt most comfortable (while complying with the aforementioned constraints). No further instructions were given.

## 2.4 Data Processing

Kinematic data was processed using Visual3D (C-Motion, Germantown, MD) and a custom-written MATLAB (MathWorks, Natick, MA) program. Marker data was gap-filled and passed through a low-pass Butterworth filter with a cut-off frequency of 6 Hz. The position of the COM was estimated using Visual3D as the centre of a pelvis model created from the pelvis markers and the bilateral greater trochanter markers. Heel-strike and toe-off gait events were identified in MATLAB using the calcaneus and 2nd metatarsal markers, respectively. All gait events were visually inspected to verify event detection and corrected as necessary.

## 2.5 Data Analysis

### 2.51 Lateral Margin of Stability (MOS)

We calculated the minimum lateral MOS for the stance phase of the first right step for trials when the target did not shift location (Straight walking) and only Null forces were applied (30 Baseline environment trials, 30 Complex environment trials) (Fig. 2A). The minimum MOS is a function of the extrapolated COM (XCOM) and the base of support (BOS), as defined in Eq (1):

$$MOS = BOS - XCOM \qquad \text{Eq (1)}$$

$$\text{where } XCOM = COM + \frac{V_{COM}}{\omega_0},$$

where $V_{COM}$ is the lateral COM velocity and $\omega_0 = \sqrt{\frac{g}{l}}$ where $g$ is the acceleration due to gravity and $l$ is the pendulum length (leg length) of the participant (12).

The magnitude of a lateral impulse required to move the XCOM beyond the lateral BOS increases proportionately with the minimum lateral MOS. Thus, increases in the minimum lateral MOS indicate increased resistance to lateral impulses.

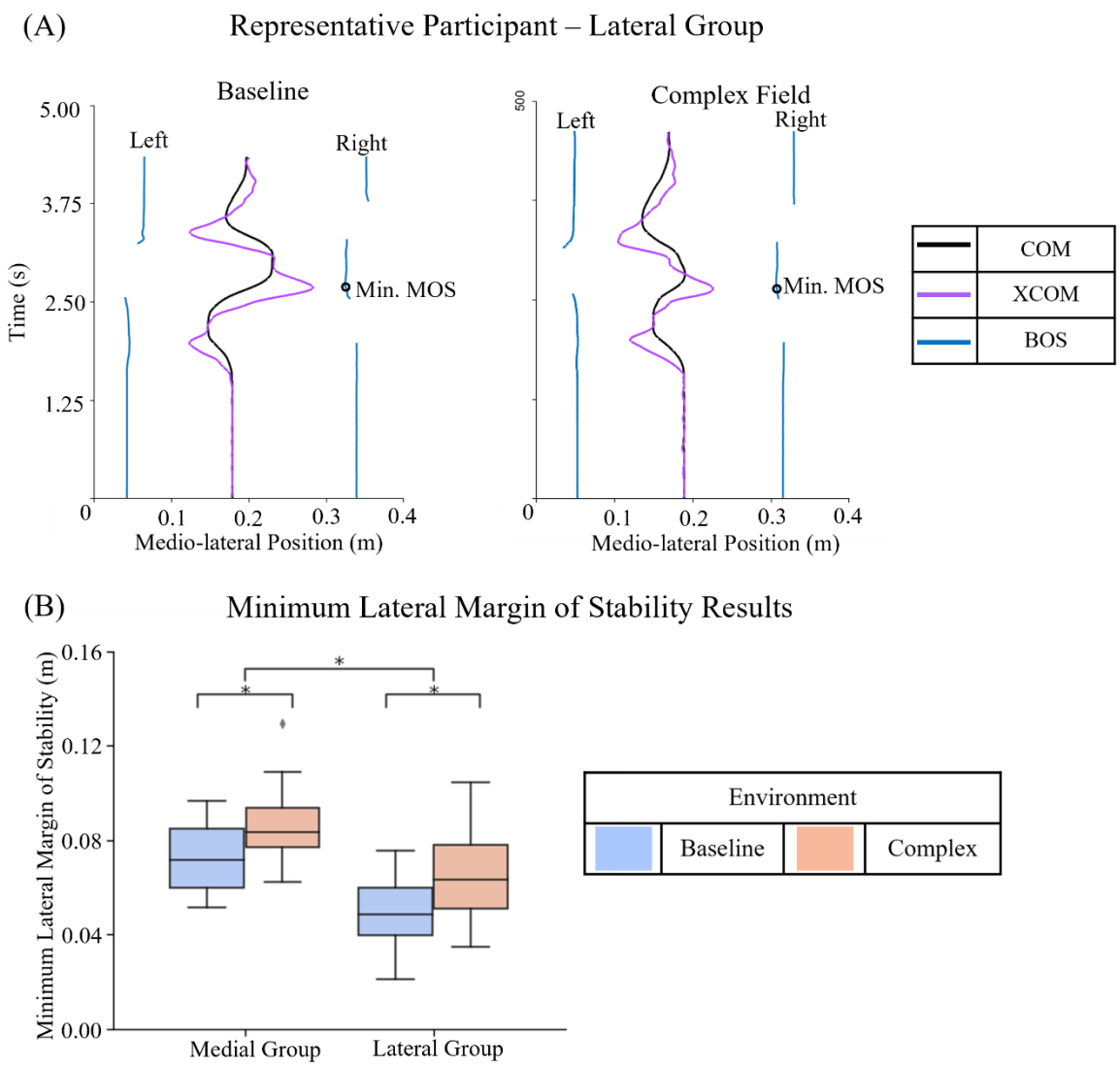


**Figure 2.** Lateral Margin of Stability (A) Representative Participant: Minimum lateral margin of stability calculation during selected trials during baseline and the complex environment. Please be aware that on this specific complex environment trial, no external medio-lateral forces were applied to the participant. (B) Group Data: Box plots and statistical results for minimum lateral margin of stability. Significance ($p<0.05$) is denoted by *.

## 2.52 Manoeuvre Reaction Time

To quantify manoeuvre reaction time ($\tau_{reaction\ time}$), we analysed only trials during which Null forces were applied and the end target shifted (30 Baseline, 30 Complex). Manoeuvre reaction time was defined as the time when the participants' manoeuvre trajectory in a Target Shift trial first differed from a Straight

trial (Fig 3A). To make this estimate, we first calculated a 95% confidence interval (CI) of the COM trajectories for Straight trials that occurred with Null forces in both the Baseline and Complex environments. Then, for the COM trajectory of each Target Shift trial in each environment, a deviation time ( $\tau_{deviation}$) was defined as the time when the COM trajectory moved outside of that environment's Straight trial CI in the same direction as the end target shift. If no deviation occurred, the time of deviation was assigned a value equal to the time required to complete the trial. To standardize the manoeuvre reaction time across each trial and participant, we used the time of target shift ($\tau_{target\ shift}$) as the cue for participants to begin the manoeuvre. Thus, manoeuvre reaction time for each trial was calculated as shown in Eq (2).

$$\tau_{reaction\ time} = \tau_{deviation} - \tau_{target\ shift} \qquad \text{Eq (2)}$$

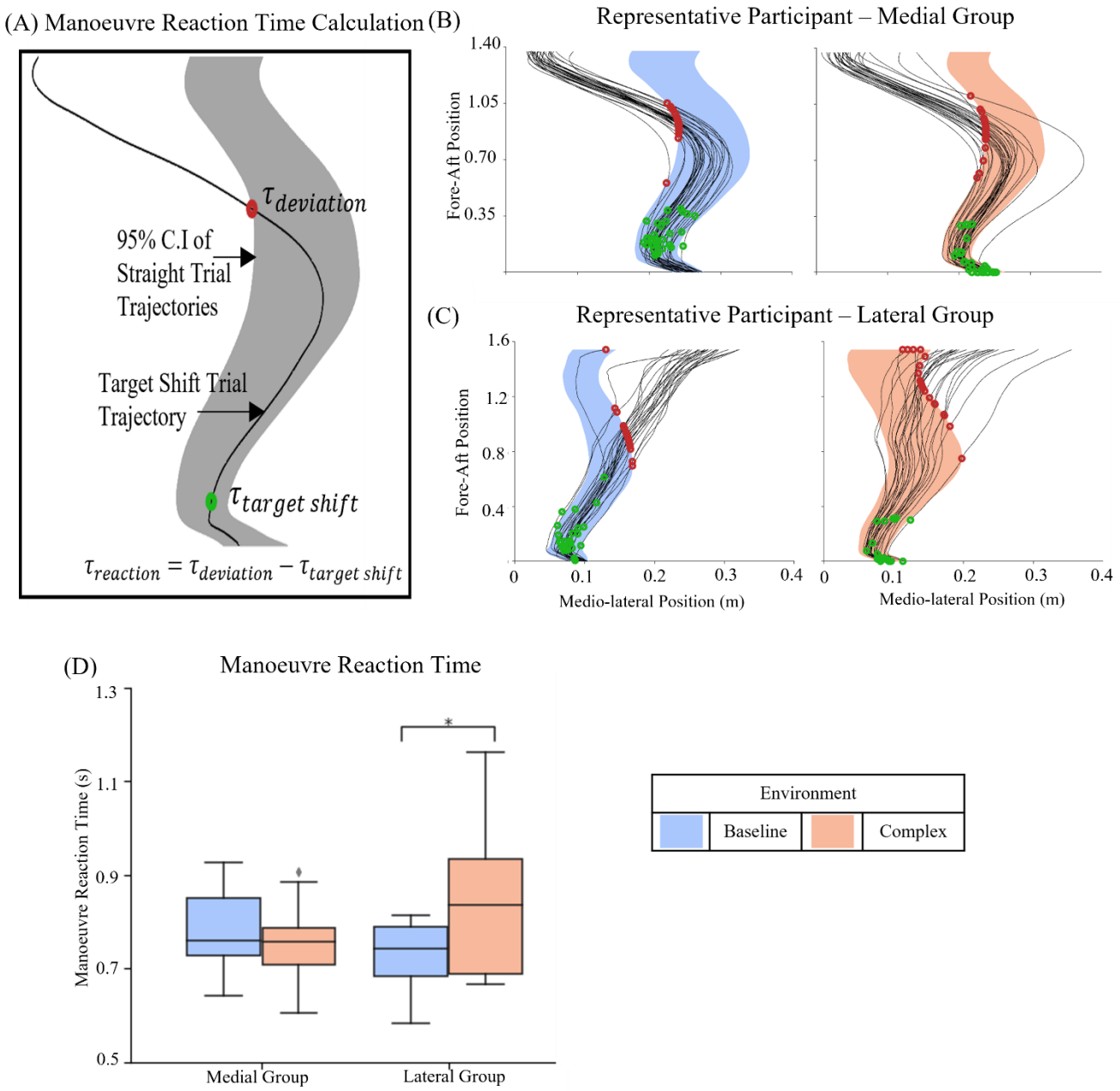


**Figure 3.** Manoeuvre Reaction Time (A) Reaction Time Calculation: Calculation of reaction time for a representative participant for a single left Target Shift trial. The shaded region represents the 95% confidence interval of all Straight-walking COM trajectories in either Baseline or the Complex environment. The black line represents the COM trajectory for a single Target Shift trial for a participant in the Medial group. (B) Representative Participant: COM trajectories for all Target Shift trials for a representative participant from the Lateral group. The green dots indicate the time when the target shifted for a trial. The red dots represent the point of deviation of a Target Shift trial COM trajectory from the confidence interval of Straight-walking trials (C) Representative Participant: COM trajectories for all Target Shift trials for a representative participant from the Medial group. (D) Group Data: Box plots and statistical results for maneuver reaction time. Significance ($p<0.05$) is denoted by *.

## 2.53 Foot Placement Error

To gain insight into how accurately participants were able to reach the end targets, we calculated a cumulative foot placement error value from the relative final locations of both the left and right foot relative to the left and right end target locations (Fig 4A). Like manoeuvre reaction time, we analysed only trials where Null forces were applied and the end target shifted (30 Baseline environment trials, 30 Complex environment trials). Foot placement error was determined as the Euclidean distance between the centre of the foot and the centre of the respective end target. The centre of the foot was defined as the centroid of a polygon formed using the markers on the 2nd and 5th metatarsals and the calcaneus. The centre of the target was the centroid of the elliptical target for each foot. The error for a trial was defined as the absolute sum of the Euclidean distances for both feet.

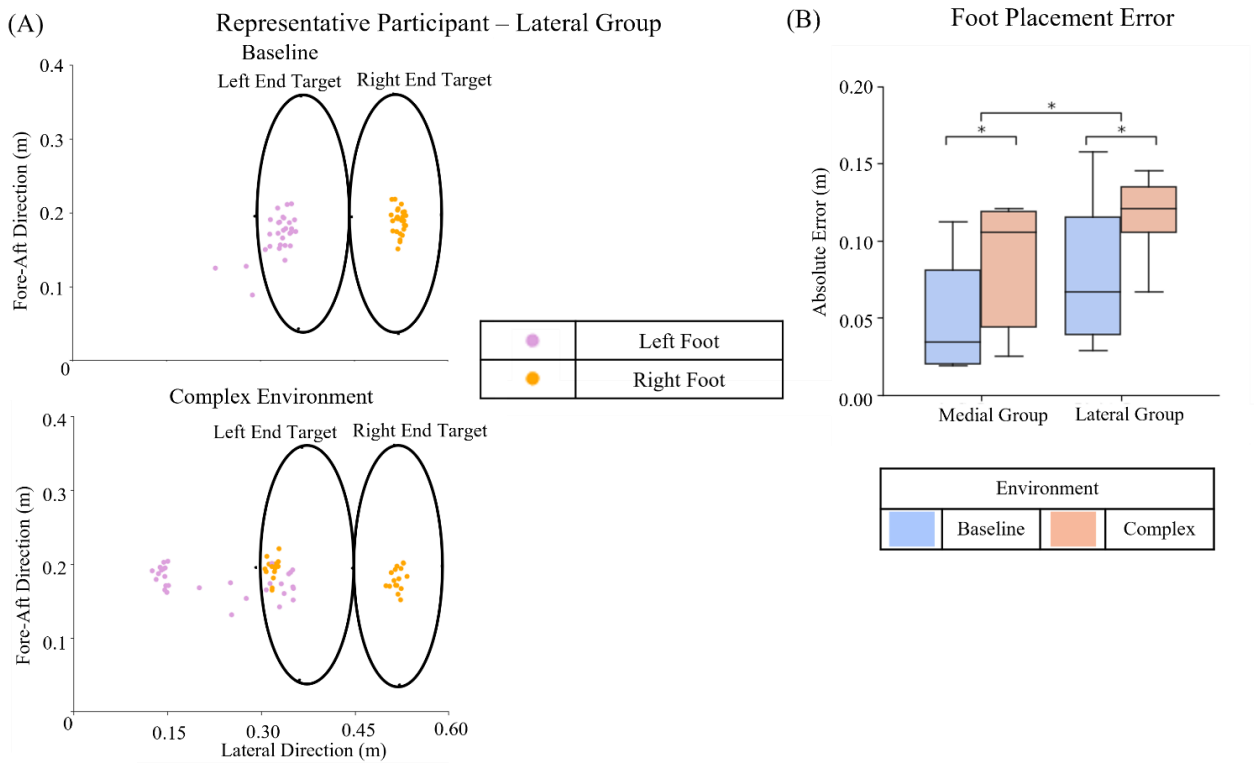


**Figure 4.** Foot Placement Error (A) Representative Participant: Foot placement for all Target Shift trials for a representative participant from the Lateral group. (B) Group Data: Box plots and statistical results for foot placement accuracy. Significance ($p<0.05$) is denoted by *.

## 2.54 Step Width and Step Length

We calculated step width and step length for the first right step on each trial to gain a better understanding of the strategies people were using to generate stability and manoeuvrability. Both metrics were calculated using the location of the centre of the foot at the start of the trial and the location of the centre of the foot at the time point of their minimum lateral MOS. Step width was defined as the mediolateral distance between the centre of the foot at the start of the trial and during stance phase and step length was the fore-aft distance for the same. Step width and step length values were normalized to leg length for each participant.

## 2.6 Statistical Analysis

The number of participants was selected based on an *a priori* power analysis conducted assuming repeated-measures ANOVA examining within-between interactions. We used an effect size of 0.48 obtained from pilot trials, 95% power, and two groups with two factors. The power analysis indicated that 9 participants in each group were required. We chose a slightly larger sample size than that calculated in the power analysis to be conservative as the effect size chosen was based on a small sample size.

As the application of mediolateral forces during the Complex environment can directly influence a manoeuvre, only trials where Null forces were applied were processed and analysed. To evaluate the effect of the environment, Null force trials in the Baseline and Complex environments were compared.

To detect differences in the minimum lateral MOS between Baseline and Complex environments, we calculated an average value for each participant from the 30 Straight trials performed during Baseline and from the 30 Straight trials performed during Null trials in the Complex environment. We performed a repeated-measures mixed ANOVA with a between factor of group (Medial or Lateral manoeuvre) and

within factor of environment (Baseline or Complex) to evaluate differences in the minimum lateral MOS. When a significant main effect of environment was found, pairwise t-tests comparisons were made.

To detect differences in the manoeuvre reaction time between Baseline and Complex environments, we calculated an average value for each participant from the 30 end Target Shift trials performed during Baseline and from the 30 end Target Shift trials performed during Null trials in the Complex environment. We performed a repeated-measures mixed ANOVA with a between factor of group (Medial or Lateral manoeuvre) and within factor of environment (Baseline or Complex) to evaluate differences in the manoeuvre reaction time. When a significant main effect of environment was found, pairwise t-tests comparisons were made.

To detect differences in the foot placement error between Baseline and Complex environment, we calculated an average value for each participant from the 30 Target Shift trials performed during Baseline and the 30 Target Shift trials in the Complex environment. We performed Kruskal tests with a between factor of group (Medial or Lateral) and Friedman tests with a within factor of environment (Baseline or Complex). When a significant main effect of environment was found, pairwise Wilcoxon tests were conducted.

All statistical analyses were conducted using the Pingouin package in Python (20). Significance was set at $p<0.05$ for all analyses. When multiple comparisons were made, a Bonferroni correction was applied.

## 3.0 Results

All 24 enrolled participants were able to successfully complete the full experimental protocol. All participants' data were included in the analyses.

### 3.1 Lateral Margin of Stability

The minimum lateral MOS was significantly larger in the Complex environment than Baseline ($p<0.001$, ANOVA) and was larger for the Medial group than the Lateral group ($p=0.0024$, ANOVA) (Fig 2B). Minimum lateral MOS increased from 0.072±0.014 m during Baseline to 0.086±0.017 m during Complex environment trials for the Medial group (Bonferroni corrected-$p=0.0070$, Paired t-test). Minimum lateral MOS also increased from 0.048±0.015 m during Baseline to 0.06±0.019 m during Complex environment trials for the Lateral group (Bonferroni corrected-$p=0.0035$, Paired t-test). Post-hoc analysis revealed that the lateral COM velocity was significantly larger for the Lateral group than the Medial group ($p=0.011$, ANOVA) but there was no significant difference between the Complex environment and Baseline ($p=0.29$, ANOVA). Lateral COM velocity was 0.15±0.034 m/s during Baseline and 0.15±0.036 m/s in the Complex environment for the Medial group. For the Lateral group, lateral COM velocity was 0.20±0.042 m/s in Baseline and 0.19±0.048 m/s in the Complex environment.

### 3.2 Manoeuvre Reaction Time

Statistical analysis revealed a significant main effect for the environment ($p=0.048$, ANOVA) but not group ($p=0.80$, ANOVA) (Fig. 3D). An interaction effect ($p=0.0045$, ANOVA) was found between environment and group. The paired t-tests found significantly delayed manoeuvre reaction times in the Complex environment than Baseline when manoeuvring laterally (Bonferroni corrected-$p=0.023$, Paired t-test). There were no significant differences in manoeuvre reaction time between the Complex environment and Baseline when manoeuvring medially (Bonferroni corrected-$p=0.59$, Paired t-test). Manoeuvre reaction time increased from 0.73±0.075 s during Baseline trials to 0.83±0.14 s in Complex environment for the Lateral group. Manoeuvre reaction time was 0.78±0.083 s during Baseline trials and 0.76±0.078 s in Complex environment for the Medial group.

### 3.3 Foot Placement Error

Statistical analyses revealed that foot placement was less accurate in the Complex environment than Baseline ($p<0.001$, Friedman) and was less accurate for the Lateral group than the Medial group ($p=0.0054$, Kruskal) (Fig. 5B). The distance between the centre of the foot and target increased from 0.08±0.044 m during Baseline to 0.11±0.023 m in the Complex environment for the Lateral group (Bonferroni corrected-p =0.013, Wilcoxon). The distance between the foot and target also increased from 0.049±0.032 m during Baseline to 0.082±0.038 m in the Complex environment for the Medial group (Bonferroni corrected-p <0.001, Wilcoxon).

### 3.4 Step Width and Length

Statistical analyses did not find significant differences in step width between stepping trials in either environment ($p=0.68$, Friedman), or between groups ($p=0.099$, Kruskal).

Step length was longer in the Lateral group than Medial, and shorter in the Complex environment than during Baseline for the Lateral group. We found a significant difference between group ($p<0.001$, Kruskal) and within environment ($p=0.041$, Friedman) for step length. The normalized step length decreased from 0.86±0.056 leg lengths during Baseline to 0.82±0.054 leg lengths in the Complex environment for the Lateral group (Bonferroni corrected-p<0.001, Wilcoxon) and was 0.77±0.0323 leg lengths during Baseline and 0.77±0.043 leg lengths in the Complex environment for the Medial group (Bonferroni corrected-p =1, Wilcoxon).

## 4.0 Discussion

We investigated how gait adaptations that increase lateral stability affect the ability to perform laterally and medially directed manoeuvres during walking. We hypothesized that increasing the lateral MOS—a common gait adaptation for increasing lateral stability—would impair the ability to make lateral manoeuvres but facilitate medial manoeuvres. Our findings support our hypothesis—increasing lateral

MOS delayed manoeuvre reaction time and decreased foot placement accuracy for lateral manoeuvres but did not affect medial manoeuvres. This outcome suggests the stability-manoeuvrability trade-off during human walking is directional. Specifically, body positioning strategies that enhance resistance to laterally directed forces during walking will impede the ability to volitionally perform lateral manoeuvres while being advantageous for performing medial manoeuvres.

### 4.1 Lateral Margin of Stability

We found participants increased their minimum lateral MOS in response to two factors; the possibility of receiving a medio-lateral perturbation, and the possibility of having to initiate a medially-directed manoeuvre.

All participants increased their minimum lateral MOS when performing the stepping task in the Complex environment when compared to Baseline. Increasing the minimum lateral MOS in the Complex environment increases the body's passive resistance to lateral directed perturbations. This occurs because the gravitational moment about the ankle-joint in the frontal plane that acts to accelerate the COM medially increases as the distance between the XCOM and the lateral base of support increases (21). Our observation that people increased their lateral MOS in response to lateral perturbations was consistent with several prior studies that also observed increases in lateral MOS when people walked in environments where they were exposed to unpredictable lateral perturbations (13,14).

We also found the group required to make Medial manoeuvres had a significantly larger lateral MOS during the first step of the task (always the right limb in stance phase) than the group required to make Lateral manoeuvres. The effect was observable even in the Baseline environment. This suggests that people may modulate their lateral MOS directly in response to the potential need to initiate a medially-directed manoeuvre. Increasing the minimum lateral MOS acts to accelerate the COM medially (away

from the stance limb) (21). An increased lateral MOS on the right limb should be beneficial for initiating a medial manoeuvre because this body position will act synergistically with any medially-directed ground reaction force impulse to initiate a medial-directed manoeuvre. In addition, when compared to a foot placed directly below the pelvis, placing the right limb lateral to the body allows the relatively large extensor muscles of the hip, knee, and ankle joints to assist the manoeuvre by generating a laterally-directed ground reaction force (GRF) (18). In contrast, increasing the lateral MOS of the stance limb should be counterproductive for initiating laterally-directed manoeuvres because 1) it increases the GRF impulse needed to initiate a laterally-directed manoeuvre, and 2) it places the stance limb in a less desirable location to generate a laterally directed GRF impulse because the large lower-limb extensor muscles will not be positioned to assist.

The lateral MOS is affected by step width as well as the lateral COM excursion and velocity. Although there was no significant difference between groups for step width, the lateral COM velocity was significantly lower overall for the Medial group. This may have been a contributing factor to the larger MOS, as the extrapolated centre of mass will decrease as velocity decreases. This suggests that participants were using different control strategies to adapt their COM trajectory in response to not only the Complex environment, but also the direction of target shift.

In this study, we quantified lateral MOS during the first step of the task in each environment (Baseline and Complex) only during trials when both the end target did not shift position and only null forces were applied. As participants were 1) not informed of target shifts or the forces they would experience and 2) the onset of both target shifts and random forces did not begin until forward walking was initiated, we believe that the lateral MOS during the first step is representative of a stepping strategy participants adapted in anticipation of the environment. However, it is possible that participants may have been able to modulate their lateral MOS after beginning forward stepping if they realized that the end target was not

going to shift, or that random forces would not be applied. If this were the case, the effect would be to decrease the lateral MOS which contrasts with our observation that lateral MOS increased. Thus, our major conclusion that MOS increased in the Complex environment is unlikely to have been affected.

### 4.2 Manoeuvrability (Manoeuvre Reaction Time and Foot Placement Error)

We observed a significant increase in manoeuvre reaction time in the Complex environment when compared to Baseline for lateral manoeuvres. In contrast, we found no significant difference in manoeuvre reaction time between the Complex environment and Baseline for medial manoeuvres. As described earlier, the manoeuvre reaction time outcomes can be explained by the increase in lateral MOS observed in the Complex environment. For the Lateral group, an increase in lateral MOS of the right limb in the Complex environment may have resulted in a longer manoeuvre reaction time because this body position resisted the participants' volitional efforts to manoeuvre laterally. This phenomenon, commonly referred to as a stability-manoeuvrability trade-off, has been observed during locomotion of many species (7,8,22). This trade-off occurs because an increase in stability (resistance to external perturbations) also results in an increased resistance to volitional changes to the body's movement trajectory (15).

In contrast, we did not observe a stability-manoeuvrability trade-off for the Medial group. For this group, increasing the lateral MOS on their right limb resulted in a body position that was favourable for both resisting lateral perturbations and making medial manoeuvres. Therefore, our findings suggest that during human walking in the frontal plane the stability-manoeuvrability trade-off is directional.

There are other factors in addition to lateral MOS that may have increased manoeuvre reaction time for Lateral manoeuvres but not for Medial manoeuvres. One explanation for this observed directionality may be the inherent anthropometric challenges of performing a laterally-directed manoeuvre. Participants may have found it more difficult to perform a "cross-over" step to manoeuvre to a laterally shifted target than

to perform a side-step to manoeuvre to a medially shifted target. Previous research suggests that people struggle to initiate manoeuvres in stepping tasks when the signal to manoeuvre is given on a step that is on the same side as the manoeuvre direction (23). Therefore, the Medial group may have found it less challenging to manoeuvre during a Target Shift trial than the Lateral group.

Another explanation is that the shorter steps observed for the Medial group than the Lateral group may have increased manoeuvrability. Prior research finds that shorter steps increase lateral stability (11). This body positioning also allows for easier stepping movements of the Medial leg into the target for medially-directed manoeuvres. Research suggests that a single-step task involving a target shift is significantly more challenging both for a condition without external stability support and for a target shift to the opposite side of the reaching foot (10). Thus, the increased stability due to the shorter steps and a less challenging manoeuvre direction may have made it easier for the Medial group to make medially-directed manoeuvres.

Increases in cognitive load induced by the Complex environment may have also affected manoeuvre reaction time. Hick's law states that as the number of stimuli increases, choice reaction time will increase proportionally (24). In accordance with this, the time needed to react to the target shift in the Complex environment will increase with the added stimuli (i.e., visuomotor coordination complexity combined with maintaining stability). Prior studies find delays in reaction time in reaching studies with destabilizing environments (25), in virtual walking environments (26), and latencies in motor adaptation in both reaching tasks and walking, which may account for an inherent delay in movement due to the complex environment (25,27). Thus, this delayed lateral-directed manoeuvre reaction time in participants could have been due to a combination of cognitive load and latency due to the uncertainty in the environment. Although the experimental design was similar for the two groups, if manoeuvring laterally was a more complex task (cross-over step vs side step, greater balance requirements) than manoeuvring medially, this may have also resulted in a greater cognitive load and ultimately a slower manoeuvre reaction time.

In addition to delays in manoeuvre reaction time, we also observed that the accuracy of foot placement in Target Shift trials was worse in the Complex environment than Baseline for both groups. Additionally, foot placement accuracy was higher overall for the Medial group. One explanation is the higher passive lateral stability in the Medial group, again relating to the stability-manoeuvrability directionality. Prior research suggests that for stepping tasks involving a target shift, the presence of external support (added stability) improves accuracy (10,28). In our study, as participants in the Medial group had a higher MOS on the first right step, the added passive stability may have allowed them to make more accurate steps to the target. If participants in the Medial group we more stable, they may have been better able to prioritize the task of being accurate while manoeuvring. Another explanation is that this directionality may be due to a more challenging task for the Lateral group. Previous research shows larger absolute errors in stepping tasks where the target shifts to the opposite side of the stepping foot (10). In our case, this would mean that a target shift to the right may have been more challenging for participants to manoeuvre to, as the first foot entering the end target was their left foot.

## 5.0 Conclusion

The present study evaluated the interaction between stability and manoeuvrability during walking in complex environments. Overall, we found that the stability-manoeuvrability trade-off may be directional. The stability-manoeuvrability trade-off was present for laterally-directed manoeuvres but not for medially-directed manoeuvres in our study. Our results may provide a framework to better understand the training and retention of manoeuvres during human walking.

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## 9.0 Data Availability Statement

The data are available at https://doi.org/10.21985/n2-g778-5k68.