Compensations for increased rotational inertia during human cutting turns

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SUMMARY

Locomotion in a complex environment is often not steady-state, but unsteady locomotion (stability and maneuverability) is not well understood. We investigated the strategies used by humans to perform sidestep cutting turns when running. Previous studies have argued that because humans have small yaw rotational moments of inertia relative to body mass, deceleratory forces in the initial velocity direction that occur during the turning step, or “braking” forces, could function to prevent body over-rotation during turns. We tested this hypothesis by increasing body rotational inertia and testing if braking forces during stance decreased. We recorded ground reaction force and body kinematics from seven participants performing 45° sidestep cutting turns and straight running at 5 levels of body rotational inertia, with increases up to 4-fold. Contrary to our prediction, braking forces remained consistent at different rotational inertias, facilitated by anticipatory changes to body rotational speed. Increasing inertia revealed that the opposing effects of several turning parameters including rotation due to symmetrical anterior-posterior forces result in a system that can compensate for 4-fold changes in rotational inertia with less than 50% changes to rotational velocity. These results suggest that in submaximal effort turning, legged systems may be robust to changes in morphological parameters, and that compensations can involve relatively minor adjustments between steps to change stance initial conditions.

Short title: Bipedal maneuverability

Key Words:
Locomotion, stability, maneuverability, unsteady, sidestep, motor control
INTRODUCTION

Maneuverability is necessary for locomotion in natural environments (Jindrich and Qiao, 2009). Maneuvers involve behaviorally-generated changes to speed, direction, and/or body orientation. Animals must maneuver to forage, negotiate uneven terrain, or escape predation, with direct impacts on fitness (Demes et al., 1999; Dunbar, 1988; Howland, 1974; Losos and Irschick, 1996). Performance depends on morphology, behavior and motor control (Aerts et al., 2003; Alexander, 2002; Carrier et al., 2001; Dial et al., 2008; Eilam, 1994; Jindrich et al., 2006; Jindrich and Full, 1999; Jindrich et al., 2007; van Damme and van Dooren, 1999). For humans, turns alone comprise up to 50% of walking steps during daily living (Glaister et al., 2007), and can cause injuries directly by increasing the forces and moments experienced by the legs, and indirectly by decreasing stability and causing falls (Besier et al., 2001; Colby et al., 2000; Cross et al., 1989; Kawamoto et al., 2002; McLean et al., 2004; Stacoff et al., 1996). Maneuvering performance reflects dynamic interactions among mechanics, musculoskeletal physiology, and motor control (Biewener and Daley, 2007; Dickinson et al., 2000; Full et al., 2002; Jindrich and Qiao, 2009).

Determining the principles governing unsteady locomotion therefore requires assessing both the mechanical requirements and behavioral compensations associated with maneuvers.

Two common aspects of maneuvers are changing movement direction and body re-orientation. Changing movement direction requires a force impulse with a component orthogonal to the initial movement direction ($imd$). Body re-orientation does not require external moments if large limb motions are used (Kane and Scher, 1970). However, moments due to external forces will also cause rotation if resultant forces are not directed through the center of mass (COM). For example, a simple mathematical model based on the assumptions that 1) rotational moments are primarily due to external forces, and 2) that body rotation should align with velocity direction at the end of a turning step, can predict horizontal-plane ground-reaction forces (GRFs) used during maneuvers in insects, ostriches, and humans (Jindrich and Qiao, 2009). The model relates several morphological (i.e. body mass, $M$, yaw moment of inertia, $I_{zz}$), task (i.e. velocity direction change, $\theta_d$), amount of
body rotation, \( \theta_r \), and speed, \( V_{AEP,imd} \) and behavioral (i.e. fore-aft foot placement, \( P_{AEP,imd} \), lateral foot placement, \( P_p \), and stance duration, \( \tau \)) parameters (Fig. 1A). The model was used to express the hypothesis that braking forces, i.e. deceleratory forces in the initial velocity direction that occur during the turning step, act to control body rotation during running turns (Jindrich et al., 2006). Specifically, the model suggests that braking forces prevent body over-rotation in humans, in part due to an orthograde posture and high ratio of \( M \) to \( I_{zz} \). This hypothesis was supported by the 7-20 fold increases in braking forces during turns relative to constant-average-velocity (CAV) running, the approximate doubling of average braking forces with an increase in turn magnitude from 28° to 42°, and the high (\( r^2 = 0.7 \)) correlation between measured and model-predicted peak braking forces for both sidestep and crossover cuts (Jindrich et al., 2006).

Additional support was provided by the model’s prediction that braking forces for ostriches, ancestrally cursorial runners with a pronograde posture and a lower ratio of \( M \) to \( I_{zz} \) relative to humans, may not be necessary to prevent over-rotation (Jindrich et al., 2007). As predicted by the model, ostriches made sidestep cuts using braking forces that were, on average, close to zero. Although the lower \( M \) to \( I_{zz} \) ratio could explain some of the low braking forces observed in ostriches, differences in several other parameters also contributed (Jindrich and Qiao, 2009). Although measured peak braking forces were tightly correlated to predictions (\( r^2 = 0.7 \)), forces also showed substantial variance across trials, suggesting that braking forces may still contribute to trial-by-trial control of body rotation.

In addition to braking forces, other behavioral parameters could also contribute to successfully matching changes in body orientation to changes in velocity direction during running turns. For humans, turns of increasing magnitude were associated with increases in stance duration (\( \tau \)) and foot placement in the anterior-posterior (\( P_{AEP,imd} \)) and medio-lateral (\( P_p \)) directions. However, these changes were not as closely associated with turn magnitude as were braking forces (Jindrich et al., 2006). Moreover, several parameters that could affect turning were not included in the analysis or model. For example, body rotation could be directly affected by initial pre-rotation angle (\( \theta_i \)) and initial body rotational speed (\( \omega_0 \); Fig. 1A). Rotation due to free moments (\( \theta_{T_z} \)), i.e. rotation due to moments directly
generated by the foot in contact with the ground, were small during normal running turns, but could potentially be recruited under different or perturbed turning conditions. Consequently, whether adjustments to one, or some combination of, these parameters are used to control body rotation during running turns remains a question.

One difference among parameters that could affect their role is when each parameter can be altered in the stride cycle. Changes to braking force, free moment, or stance duration involve alterations to forces or moments generated by the leg during stance. Changes to other parameters (e.g. $P_{AEP,\text{ind}}$, $P_{p}$, $\theta_{i}$, or $\omega_{0}$) involve altering leg or body kinematics during previous steps or the flight period before stance. Anticipation can involve adjustments to muscle activity associated with changes in foot placement and ground-reaction forces (Bencke et al., 2000; Houck, 2003; Rand and Ohtsuki, 2000). However, passive factors such as coupling among parameters (i.e. foot placement and GRFs) could also contribute to changes prior to turning steps. For simplicity, we will term “anticipatory” any parameters that are determined before the turning step, whether passive (mechanical) or active factors primarily cause a change. Furthermore, observed anticipatory changes may not necessarily be involved in the trial-level control of individual turns, but could instead reflect task-level adjustments associated with the shift from CAV running to turning (Besier et al., 2003). Consequently, the role of anticipatory adjustments relative to changes that occur during the stance period of a turning step remains unclear.

Our overall goal is to better characterize the behavioral strategies used by legged animals to perform turning maneuvers: to identify the parameters used to turn and determine how and when they are modulated to make successful turning maneuvers despite variability and perturbations. Specifically, we sought to test the hypothesis that human runners use braking forces alone to maintain appropriate body rotation during running turns under different mechanical conditions that affect body rotation. This hypothesis would be supported if perturbations that affect body rotation result in proportional changes to braking forces during stance, but do not affect other behavioral parameters. If braking forces do not change then the hypothesis is rejected, and this presents the question of whether anticipatory adjustments, within-step changes, or a combination are used to compensate for
perturbations to rotation.

To test this hypothesis, we sought to perturb body rotation requirements while minimally changing other aspects of turning (i.e. requirements for movement direction or linear momentum change). To this end, we used a harness system that enabled up to 400% increases in rotational inertia with substantially less (15% ~ 17%) changes to body mass. If the magnitude of braking forces alone are adjusted to control body rotation, the turning model predicts that increases in $I_{zz}$ would progressively decrease peak braking forces and even result in acceleratory forces. Three-fold increases in $I_{zz}$ would decrease peak braking forces to zero, and similar to ostriches, humans would turn using primarily the average lateral forces necessary for movement deflection.
MATERIALS AND METHODS

All procedures used for these experiments were approved by the Institutional Review Board of Arizona State University.

Turning model

The model (Fig. 1A) assumes that an individual approaches touch down (TD) at a horizontal speed of $V_{AEP,imd}$ (AEP, anterior extreme position; imd, initial movement direction) and makes a turn that changes COM velocity direction by $\theta_d$ over a stance duration of $\tau$. Relative to the COM, the foot is placed a distance of $P_p$ in the medio-lateral (ML) direction, and $P_{AEP,imd}$ in the anterior-posterior (AP) direction. The foot generates a half-sine shaped ML force, $F_p(t)$, with peak of $F_{p,max}$, and an AP force, $F_{imd}(t)$, that is the superposition of a full sine wave (with a peak of $\alpha$) and half-sine acceleratory or deceleratory force (peak $\beta$; Fig. 1C; (Jindrich et al., 2006). Because the foot is initially placed anterior to the COM and moves posteriorly relative to COM during stance, $F_p(t)$ causes a moment that initially rotates the body in the turning direction, but rotates against the turning direction after approximately mid-stance. The “leg effectiveness number” ($\varepsilon$) is defined as the body rotation caused by $F_p(t)$, $\theta_{fp}$, relative to the COM deflection angle, $\theta_d$ (Eq. 1). Peak acceleratory/deceleratory force, $F_{hmax}$, is the model prediction of $\beta$, and can be calculated by Eq. 2 (Jindrich et al., 2006).

\begin{align}
\varepsilon &= \frac{\theta_{fp}}{\theta_d} = \frac{MV_{AEP,imd}\tau}{2I_{zz}} \left( P_{AEP,imd} - \frac{4V_{AEP,imd}\tau}{\pi^2} \right) \\
F_{hmax} &= \frac{\pi I_{zz}(1-\varepsilon)\theta_d}{\pi^2 P_p} 
\end{align}

Predicted and measured deceleratory forces, $F_{hmax}$ and $\beta$, were defined to be negative and acceleratory forces positive. Assumptions of this model include 1) successful turns involve body rotation ($\theta_r$) matching $\theta_d$ at the end of the turning step; and 2) initial body pre-rotation angle ($\theta_i$), and angular speed ($\omega_0$) are zero (Fig. 1A).

For humans, the $\varepsilon$ during running cuts ranges from approximately 2–4 (Jindrich et al., 2006). Consequently, during turns the difference (1- $\varepsilon$) in Eq. 2 is typically negative, resulting in negative (“braking”) $F_{hmax}$. Increasing $I_{zz}$ would be expected to reduce $\varepsilon$, in turn
reducing \((1-\varepsilon)\) and therefore reducing the braking forces required for \(\theta_r\) to match \(\theta_d\) at the end of the step.

Participants and anthropometric data

Seven participants (age = 22.5±1.5 yrs; body mass \((M) = 68.2±4.0kg\); body height \((bh) = 174.9±4.2cm\), leg length = 96.1±4.6cm, 5 males; mean±std) participated in the study. Anthropometric data for individual participants were estimated using allometric scaling from a reference human model, assuming identical density and segment mass percentage (Herr and Popovic, 2008; Huston and Passerello, 1982). The principal moments of inertia of each segment in yaw, roll and pitch directions were then scaled. Whole body moment of inertia tensor relative to the COM in the stance posture, as a function of \(M\) and bh, was calculated using the parallel axis theorem. This resulted in body rotational inertia, \(I_{zz}\), scaling with \(M^{5/3}\) (Carrier et al., 2001). The participant’s body rotational inertia about the vertical axis was validated by having participants make stationary turns on a force platform, and calculating \(I_{zz}\) using a least-squares fit to free moment and rotation angular acceleration (validation \(R^2 = 0.72\); (Jindrich et al., 2007).  

Harness

A customized harness (8.3kg) based on previous designs was built using galvanized steel bars and a rigid plastic frame (Carrier et al., 2001). The harness was used to change \(I_{zz}\) by adding equally balanced weights (tiny lead balls contained in a bag) both anterior and posterior to the COM (Fig. 1B). The dimensions of the harness were 0.7 (ML) × 1.5 (AP) × 0.8 (z) m. Treated as a rigid body, its principal moments and products of inertia were 1.35 (ML), 0.100 (ML, AP), 0.463 (ML, z), 0.601 (AP, z), 0.0972 (AP, z), and 1.38 (z) kg·m², determined by measuring swinging periods about principal axes and the parallel axis theorem (Jindrich and Full, 1999).  

Moment of inertia increase
Five different harness mass and $I_{zz}$ increment combinations were applied: $M0%I1$ (control, no harness, NH), $M15%I3$ (mass increased by 15% and body inertia to 3-fold), $M15%I3.5$, $M17%I3.5$, and $M17%I4$. To change $I_{zz}$, mass was attached to the horizontal bars symmetrically about the COM of the combined human and harness. The added weight was selected so that the total weight with the harness was a set percentage (15% or 17%) of the participant’s $M$. Both weight and position were changed to achieve the target body mass and $I_{zz}$ increments. For example, for the $M15%I3.5$ condition, less weight was placed further from the COM, while for the $M17%I3.5$ more weight was placed closer. The specific weights and positions were calculated separately for each participant.

Experimental procedure

Participants ran at 2.98±0.08 m s$^{-1}$, and performed both straight running (RUN) and left 45° sidestep cutting turns (TURN). Turning direction was indicated by tape on the floor. In each condition, 5 trials were collected. The order of the conditions (RUN and all TURN conditions) were randomized. Participants were given instructions to make turns in a natural way, but were not instructed to maintain constant speed during the turn.

We used a 3-D motion tracking system (VICON®, model 612, Oxford Metrics, Oxford, UK) to record the kinematics of 37 reflective markers at 120 Hz. To compensate for the harness, we replaced the markers on the anterior and posterior superior iliac spines in the standard marker set with markers on the left and right greater trochanter (LGT and RGT). Two force platforms (400 × 600 mm, model FP4060-NC, Bertec Corporation, Columbus, OH, USA) embedded in the ground were used to record GRF at 3000 Hz. The inertial coordinate system was defined as in Fig. 1A. Anterior-posterior (AP) and medio-lateral (ML) directions were defined as parallel and perpendicular, respectively, to the horizontal projection of COM velocity at TD (i.e. $imd$, Fig. 1C). Forces in the AP direction can be decomposed into full-sine components similar to those observed during constant-speed running, and half-sine components only observed during turning (Jindrich et al., 2006). The full-sine ($\alpha$) and half-sine ($\beta$) components in $F_{imd}(t)$ were determined by multiple linear regression using $\alpha \sin(2\pi t/\tau)$ and $\beta \sin(\pi t/\tau)$. 
The COM was calculated by segmental average and its velocity was tuned with the GRF using a path finding algorithm (McGowan et al., 2005). Specifically, the initial velocity that minimized the Euclidean distance between the tuned and untuned COM trajectories was chosen. Body rotation ($\theta_r$) was defined as the change in the vector connecting the hip markers (LGT and RGT; Fig. 1A) over the turning step. We also tuned rotational angle with resultant vertical moment to determine the initial rotational angular speed ($\omega_0$) at the beginning of a turn. The correlation between tuned and un-tuned rotational angle trajectories was 0.99.

Because the harness was at the height of pelvis, LGT and RGT markers were not visible in some of the trials. Those trials were excluded from analysis, but at least one trial for each participant at each condition was available. Only two participant/condition sets had only one trial due to marker placement. 83% of participant/condition sets contained 5 trials. For turning, 284 trials were successful out of 420.

Kinematic data were interpolated to the same sampling frequency as GRF using a spline fit. The instant of TD was determined as the first sample after which raw vertical GRF continuously increased for 5 ms, (Qiao and Jindrich, 2012). An equivalent criterion was used to identify the last 5 ms of force decrease to identify TO. Because COP location at TD can be noisy due to impact transients, we used the average COP location during stance relative to the toe marker to calculate $P_{AEP,imd}$ and $P_p$ (Jindrich et al., 2006). Kinetics/kinematics were filtered by 4th-order-zero-lag low-pass Butterworth digital filter at 30/11 Hz.

To compare the effect of rotational inertia (different $M$ and $I_{zz}$ combinations) on turning performance we used repeated measure of Analysis of Variance (rANOVA) with participants as the repeated factor (Keppel and Wickens, 2004). To compare the effects of gait and rotational inertia on the gait parameters, a factorial rANOVA was employed with factor A the gait (TURN vs. RUN) and factor B the levels of different rotational inertias. Post-hoc analysis was based on Bonferroni procedure with Šidák correction ($p < (1-(1-\alpha)^{1/c})$, $c = (a-1)a/2$, a is the number of $I_{zz}$ levels, and this resulted in $p < 0.0051$).

All calculations were performed using MATLAB (R2012a, Math Works, Inc., Natick,
MA, USA). All values within the text and tables are mean ± standard deviation except as indicated.
RESULTS

Turning performance was similar among inertia conditions

Increasing rotational inertia did not change most aspects of turning performance. On average, participants made sidestep cuts with COM deflection angle ($\theta_d$) and body rotational angle ($\theta_r$) that were not significantly different among conditions (Table 1). However, participants did not fully deflect their movement direction by 45° during the turning step, but by only 25°~27° (Table 1). This was primarily due to partially changing movement direction (relative to global) before the primary turning step. Forces in both ML and AP directions ($F_p(t)$ and $F_{imd}(t)$, respectively) were also not significantly different (Fig. 2AB). There was no significant difference between COM initial speed ($V_{AEP,imd}$), and final speed ($V_f$) ($p = 0.99$; Table 1). Increased force impulses associated with 15~17% increases in mass were achieved by 10~16% increases in stance duration ($\tau$, Table 1). Consequently, because participants were able to achieve similar performance in all conditions, turns with and without the harness and in different $M$ and $I_{zz}$ conditions were considered comparable.

Increasing inertia did not decrease peak braking forces

Leg effectiveness number ($\varepsilon$) decreased significantly as rotational inertia increased ($p < 0.01$, Table 1). Measured decreases in $\varepsilon$ caused the predicted peak braking force, $F_{hmax}$, to decrease significantly and to predict acceleratory forces at $M17\%I3.5$ and $M17\%I4$ ($p < 0.01$, Fig. 3A, Table 1).

However, measured peak braking force, $\beta$, was not significantly different among rotational inertia conditions ($p = 0.08$, Table 1). Moreover, GRF impulse in the AP direction was also not different ($p = 0.21$, Fig. 3B). Consequently the hypothesis that increasing rotational inertia would decrease measured peak braking force was rejected.

Force direction relative to the leg did not change with increased inertia

The consistent braking forces across $M$, $I_{zz}$ conditions resulted in unchanged leg orientation with respect to GRF (1.5°) during stance. The GRF direction relative to the virtual leg connecting COM and COP at 50% of stance phase was unchanged during
sidestep cutting turns with different $I_{zz}$ (Fig. 4A, $p = 0.19$). Relative angles during straight running under different $I_{zz}$ also remained the same (Fig. 4B, $p = 0.48$). A factorial rANOV A comparing the effects of gait (Factor A, TURN and RUN) and $I_{zz}$ (Factor B) on body orientation relative to GRF revealed no main effects (Fig. 4C, $p_A = 0.9$, $p_B = 0.2$).

Both anticipatory and within-step parameters changed with increased inertia

Increased $I_{zz}$ was associated with both changes to parameters describing the turning step, and anticipatory adjustments. Significant increases in stance duration occurred during the turning step ($\tau$, $p < 0.01$, Table 1). ML foot placement ($P_p$), which reflects changes that primarily occur before the turning step, decreased 8~15% relative to non-harness (NH, $M0\%II$) turning. However, AP foot placement ($P_{AEP,imd}$) did not differ significantly among conditions ($p = 0.15$, Table 1). Changes to $P_p$ were partially due to shifts of COP under the foot. When either $P_{AEP,imd}$ and $P_p$ were determined from the toe or heel markers, there was no significant difference among inertia conditions ($P_{AEP,imd}$, $p = 0.13$; $P_p$, $p = 0.32$).

All other parameters being equal, decreases in $P_p$ would be expected to require increased peak braking force ($\beta$) (Eq. 2). However, the decreases in $P_p$ were more than offset by 10~16% increases in $\tau$ that would be expected both to decrease $\epsilon$ (Eq. 1) and directly decrease $\beta$ (Eq. 2). Consequently, changes to the modeled parameters $P_p$ and $\tau$ could not explain the unchanged peak braking forces among different rotational inertia conditions.

Changes to initial rotational velocity contributed to consistent braking forces

Increasing $I_{zz}$ revealed that a balance among several previously un-modeled parameters resulted in unchanged $\beta$ across conditions. A more complete model of turning (Appendix A) showed that perpendicular turning forces ($F_p$) and braking forces were not the only contributors to body rotation. Both the normally-observed deceleratory/acceleratory AP force (the $\alpha$ component of $F_{imd}$) and its interaction with $F_p$ resulted in substantial body rotations ($\theta_\alpha$ and $\theta_{\alpha FP}$, respectively; Table 1). For example, in the NH condition these force components together resulted in net body rotations of $-25^\circ$, i.e. against the overall turn.
direction. This rotation, $\theta_{\alpha} + \theta_{\alpha F_p}$, was almost completely offset by initial body rotational velocity ($\omega_0$) acting over the stance period, and initial body rotation ($\theta_i$) at TD, that together contributed 26° of body rotation towards the turning direction. Therefore, for the NH condition, the small amount (~1°) of net body rotation resulting from the sum of these parameters ($\theta_{\alpha} + \theta_{\alpha F_p} + \theta_i + \omega_0\tau$) did not substantially affect the ability of the simple model of Eqs. (1) and (2) to predict $\beta$ with $F_{h\text{max}}$ (Jindrich et al., 2006).

Increasing $I_{zz}$ significantly reduced both $\theta_{\alpha}$ and $\theta_{\alpha F_p}$, resulting in a combined effect of -6° to -7° of rotation against the turn direction for 3-fold and greater increases in $I_{zz}$. Without $\theta_{\alpha} + \theta_{\alpha F_p}$ opposing $\omega_0$ and $\theta_i$, the potential for body over-rotation would be expected to increase. Preventing over-rotation during the turning step could be achieved by increasing peak braking forces relative to the NH condition (opposite the hypothesis from the simple turning model) to maintain $\theta_i$ close to $\theta_d$. Instead, participants employed an anticipatory strategy, significantly decreasing $\omega_0$ (Table 1, $p < 0.05$). However, $\omega_0$ did not drop to zero but decreased only 33~49%. Therefore, rotation due to $\omega_0$ and $\theta_i$ balanced rotation due to fore-aft forces, allowing for anticipatory adjustments to initial rotation conditions to maintain nearly-constant braking forces among conditions.
DISCUSSION

Contrary to the hypothesis that increasing $I_{zz}$ would decrease braking force, we found that anticipatory changes to initial rotational speed were associated with maintaining average braking forces that did not differ among rotational inertia conditions during running turns. Consistent turning performance was maintained across 4-fold increases in $I_{zz}$ using relatively minor changes to behavioral parameters: 8~15% decreases in ML foot placement ($P_p$), 10~16% increases in stance duration ($\tau$), and 33~49% decreases in initial rotational angular speed ($\omega_0$). Moreover, the opposing rotation of multiple dynamic parameters provided humans with several behavioral options when compensating for morphological changes.

Peak braking forces did not decrease as much as predicted, maintaining consistent force direction relative to the leg

Based on the turning model and the relatively small braking forces observed in ostriches, we predicted that humans would decrease peak braking forces when the requirements for preventing body over-rotation were relaxed. Humans instead maintained similar peak braking forces and GRF orientation relative to the leg across 4-fold changes to rotational inertia. There was a trend for decreases in $\beta$ with increased inertia that may have been non-significant due to limited sample size. However, the approximately 50% decreases in measured $\beta$ would have been insufficient to explain the 150% decreases in $F_{bmax}$ predicted to control body rotation with braking forces alone. The maintenance of similar leg forces across conditions may limit the changes in motor output required for different maneuvers. Similar to ostriches, where cutting turns involved few changes to joint moments relative to straight running (Jindrich et al., 2007), humans may organize maneuvers in part to reduce functional changes at the joint or muscle level.

Several task objectives may influence the strategies used to perform maneuvers

Our simplified model relates morphological, task, and behavioral parameters based on the assumption that the body should rotate appropriately in the movement direction.
However, maneuvers may also be organized to achieve other objectives. For example, braking forces contribute to turn sharpness (Houck, 2003). Braking forces could also act to maintain consistent average speed after the turning step by offsetting the acceleration from the $F_p$ necessary to change movement direction. In support of this possibility, there was no significant difference between COM speed at TD ($V_{\text{AEP,imd}}$) and TO ($V_f$) ($p = 0.99$, Fig. 2C). For individual trials, speed at TO was correlated with speed at TD ($R^2 = 0.55$; Fig. 7A). The braking forces necessary for speed at TO to equal speed at TD can be predicted for a simple point-mass model as $m\bar{V}_{\text{AEP,imd}}(\cos \theta_d - 1)$. Braking forces required for constant speed were correlated with measured forces (slope = 0.3 and $R^2 = 0.43$; Fig. 7B). We therefore cannot reject the hypothesis that constant-speed movement is an objective. However, measured braking forces were larger than forces predicted by the point-mass model (resulting in a slope <1).

Therefore, although movement parameters are related in a way that results in appropriate body rotation and can be predicted by Eqs. (3) and (4), we cannot conclude that these relationships reflect active control of body orientation. Additional experiments will be necessary to determine how movement is organized to potentially satisfy several task objectives of potentially different importance, including controlling body rotation, maintaining speed, maximizing stability, reducing injury risk, minimizing energetic cost, or reducing sensorimotor demands.

Whether the strategies used by bipeds for maneuvers are also employed by other animals also remains an important question. Quadrupeds or polypeds that step with more than one leg may have fewer constraints, and more options for maneuvering strategies than bipeds (Jindrich and Full, 1999). For example, additional legs may allow for rotation and translation to become partially de-coupled (Walter, 2003).

*Anticipatory changes contributed to consistent peak braking forces*

Anticipatory adjustments contributed to appropriate body rotation. Increasing $I_{zz}$ resulted in significant differences in anticipatory (ML foot placement, $P_p$, and initial angular speed, $\omega_0$) parameters and to parameters describing the turning step (stance
duration, \( \tau \)). However, observed increases in \( \tau \) could be primarily due to increases in body mass (\( M \)) resulting from the harness and weights. Although our original intent for using two separate levels of added mass was to directly test the effects of \( M \) on turning, constraints on the length of the harness bars limited our values of \( M \) to differing by only 2%. Longer galvanized steel bars substantially increased \( M \) and offset the benefit of requiring less added weight to increase \( I_{zz} \). However, as \( M \) and \( I_{zz} \) increased, \( \tau \) increased 15~20% even in the RUN condition (\( p < 0.05 \), Table 2). Similarly, increasing \( M \) alone by 10% or 20% was found to result in 5% or 8% increases in \( \tau \) during constant-speed treadmill running at 3 m s\(^{-1} \) (Chang et al., 2000). Therefore, it is reasonable to conclude that the increases in \( \tau \) are associated with increased \( M \) and not \( I_{zz} \).

If increases in stance duration reflected compensations for increased mass, compensations for increased \( I_{zz} \) principally involved significant changes in two parameters that were both primarily determined before the turning step: ML foot placement (\( P_p \)) and initial body rotational speed (\( \omega_0 \)). For all turning conditions, humans increased their lateral leg placement relative to straight running (RUN), where \( P_p \) averages approximately 4 cm (Jindrich et al., 2006). The higher \( P_p \) observed during turns compared with RUN could reduce the braking forces necessary to prevent over-rotation, and would therefore be consistent with the hypothesis that humans reduce braking forces when less necessary due to increased \( I_{zz} \). However, increases in \( I_{zz} \) were instead associated with decreased \( P_p \) relative to the NH condition, consistent with the alternative hypothesis that humans use anticipatory adjustments to maintain unchanged braking forces during running turns.

In contrast to changes in ML foot placement, decreases in \( \omega_0 \) with increased \( I_{zz} \) relative to the NH condition would be expected to decrease peak braking forces. However, the values of \( \omega_0 \) were high in the NH condition (65 °/s) and remained positive despite 33~49% decreases with increased \( I_{zz} \) (Table 1). Therefore, along with pre-rotation (\( \theta_i \)), \( \omega_0 \) continued to cause rotation in the trial turn direction. Overcoming rotation due to \( \omega_0 \) contributed to required braking forces in all conditions. Without decreases in \( \omega_0 \), peak braking forces in the increased \( I_{zz} \) conditions could even have increased relative to NH values. Therefore, the decreases in \( \omega_0 \) relative to the NH condition were also consistent with the hypothesis that...
humans use anticipatory adjustments to maintain unchanged peak braking forces during running turns. Anticipatory adjustments that reflected behavioral strategies would be consistent with research on walking turns (Jindrich and Qiao, 2009). For example, anticipation in walking turns affects foot placement (Orendurff et al., 2006; Patla et al., 1999), and changes to $\omega_0$ and $\theta_i$ are initiated before the turning step in walking (Taylor et al., 2005). The finding that anticipatory compensations are used during both walking and running could therefore suggest that humans may use some feed-forward strategies to execute anticipated maneuvers.

However, because initial rotational speed reflects the dynamics of strides before the turn that could be affected by increased $I_{zc}$, we cannot determine whether decreases in $\omega_0$ were due to behavioral adjustments or stemmed passively from changes in running dynamics associated with higher $M$ and $I_{zc}$. Decreases in $\omega_0$ in the RUN condition (Table 2) for increased $I_{zc}$ suggest that the compensations necessary to maintain unchanged braking forces may arise passively, or be part of a more general strategy for compensation for increased inertia. Future experiments may be able to distinguish between robustness of the mechanical system and behavioral strategies that allow modest changes to initial conditions to compensate for large morphological perturbations.

**Coupling among morphology, dynamics, and behavior could affect the parameters chosen for compensations**

A running, segmented system involves many morphological and behavioral factors that are extensively coupled. Coupling can involve both passive mechanisms (due to changes in movement dynamics) and active coupling, where adjustments are made to achieve task requirements and mechanical or energetic objectives (Hackert et al., 2006). For example, decreased AP foot placement ($P_{AEP,imd}$) would be predicted to decrease body rotation (Eqs. 1, 2, A.10). However, decreasing $P_{AEP,imd}$ could result in transfer of potential to kinetic energy, COM acceleration, and increased speed (McGowan et al., 2005; Qiao and Jindrich, 2012). Changes to stance duration could alter both translational and rotational momentum changes about all three axes, potentially altering movement dynamics (Herr and Popovic,
We hypothesize that adjusting initial rotational speed is advantageous because changes to $\omega_0$ can directly affect body rotation, depending only on stance duration (A.10). However, this presents the question of why humans did not change pre-rotation to compensate for increased $I_{zz}$, as $\theta_i$ can also directly change net body rotation. Changes in $\theta_i$ may not have been used because $\theta_i$ influences the orientation of the leg relative to the body at touchdown, potentially requiring substantial changes in muscle activity to ensure that leg forces remain appropriate, and that resultant leg forces are minimally affected by turning.

Accounting for coupling among movement parameters and initial rotation conditions allows for refinement of the simplified model

Perturbing locomotion by increasing $I_{zz}$ demonstrated that several simplifying assumptions made in the original model (Eqs. 1 and 2) were not appropriate for a general description of horizontal-plane maneuvers.

First, the model simplified COM motion in the initial movement direction by assuming constant speed. This allowed foot movement relative to the COM to be described as $P_{imd}(t) = P_{AEPM_{imd}} - V_{AEPM_{imd}} \cdot t$ (Jindrich et al., 2006). Accounting for accelerations during stance caused by forces in the initial movement direction (Appendix: A.3) resulted in two additional terms, $\theta_a$ and $\theta_{\alpha F_p}$ (A.10). The net effect of $\theta_a + \theta_{\alpha F_p}$ would be rotation against the turning direction, leading to predictions of lower peak braking forces.

Second, the original model neglected initial body rotation conditions, initial rotational speed ($\omega_0$) and pre-rotation ($\theta_i$). Both $\omega_0$ and $\theta_i$ were positive, towards the trial turn direction, and would be expected to contribute to over-rotation and lead to a prediction of increased peak braking forces.

Third, the model also assumed that body rotation ($\theta_r$) matched movement deflection ($\theta_d$) at the end of the turn. However, total body rotation was less than movement deflection at TO across all conditions, suggesting that humans may prefer to consistently under-rotate during stance (Table 1; Fig. 5). Maintaining under-rotation would be predicted to require increased peak braking forces. Finally, the original model did not account for moments...
generated by the foot, $\theta_r$.

Accounting for these parameters allows for a more complete description of the relationships among factors that contribute to body rotation, $\theta_r$ (Eq. A.10). Using this more complete description, the leg effectiveness number can be revised to include the effects of fore-aft forces

$$LE = \frac{\theta_{FP} + \theta_\alpha + \theta_{aFP}}{\theta_d}. \quad (3)$$

The variance in peak braking forces can then be predicted based on $LE$ and a term representing the contribution of initial rotational conditions ($\omega_0, \tau$ and $\theta_i$) and the preference for under-rotation during the turning step ($\theta_f$),

$$\eta = \frac{\omega_0 \tau + \theta_i + \theta_f}{\theta_d},$$

$$F'_{h_{\text{max}}} = \frac{\pi I_{\text{zz}} \theta_d}{\tau^2 F_p} (1 - LE - \eta). \quad (4)$$

Because they are consistently small during running turns (Table 1, Fig. 5B), effects of free moments ($T_z$) have been omitted from Eq. 4 for simplicity. However, inclusion of free moments may be necessary to describe walking or other related tasks (Lee et al., 2001; Orendurff et al., 2006). The more general relationship of Eq. 4 results in better fits to measured braking forces (Fig. 3A; Fig. 6B). For these estimates, the consistent preference for under-rotation that we observed was estimated using a constant value of 4.1° for $\theta_f$.

Importantly, it is necessary to include all of these additional factors in the model. Because components act to rotate the body in different directions, addition of any single factor results in fits that are poorer than those of Equations (1) and (2).

A balance of opposing factors could contribute to the robustness of legged maneuvers

Increased rotational inertia is often assumed to limit maximal turning performance (Carrier et al., 2001; Eilam, 1994). However, we found that increasing $I_{zz}$ up to 4-fold during sub-maximal turns did not affect performance, and could be compensated with changes to a limited number of parameters. Compensations for increased $I_{zz}$ were facilitated by the opposite contributions of several factors to body rotation. The initial conditions ($\omega_0$ and $\theta_i$), and the preference for under-rotation during the turning step ($\theta_f$), opposed the effects of rotation due to fore-aft and perpendicular forces, $\theta_\alpha + \theta_{aFP}$ (Fig. 5B; Table 1).
Consequently, when increased $I_{zz}$ decreased rotation due to forces and their resulting
moments, force directions relative to the leg could be maintained by decreased $\omega_0$.
Therefore, the opposition of rotations due to $\theta_\alpha + \theta_{\alpha F_p}$, $\omega_0$ and $\theta_i$ contributed to the
robustness of the maneuvering system by allowing substantial increases to $I_{zz}$ to be
overcome by modest changes to initial rotational speed. The robustness and stability gained
from maintaining a balance of opposing factors may be analogous to the observation of
increased muscle co-activation with increasing movement accuracy demands (Gribble et al.,
2003).

Turning remains associated with high inter-trial variability

Humans maintained unchanged braking forces and consistent force direction relative to
the leg across $I_{zz}$ conditions by altering initial conditions, ML foot placement ($P_p$) and
initial body rotational speed ($\omega_0$). These findings suggest that humans are able to modulate
several parameters to maintain specific aspects of movement invariant, on average.
However, the ability to maintain consistent peak braking force ($\beta$) across rotational inertia
conditions does not explain the large variance in many parameters, including $\beta$, across trials.
For example, across-trial variance in $\beta$ was 83% of the average, std/mean. However, the
large variance observed in individual parameters contrasts with lower variance when the
coupling among movement parameters described by Eqs. 3 and 4 is accounted for (Fig. 6).
The observation of a relationship among parameters that is maintained despite large
variance in values of the parameters themselves is analogous to the pattern observed in
joint coordination during several types of movements (Scholz and Schöner, 1999). For
example during hopping, joint redundancy is used to maintain task-level parameters such as
leg length, orientation, or force invariant (Auyang et al., 2009; Yen and Chang, 2010).
Redundancy among several factors that contribute to body rotation could be exploited to
maintain desired orientation relative to movement direction at the end of the turning step.
However, the underlying source of the considerable intra-trial variability remains to be
determined.
ACKNOWLEDGMENTS

This research would not have been possible without the support of the Arizona State University Kinesiology Program, School of Life Sciences, and Graduate College. We are grateful to James Abbas and the ASU Center for Adaptive Neural Systems for use of laboratory facilities. Furthermore, we thank Carolyn Westlake for valuable input and contributions to experimental design.

FUNDING

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# LIST OF SYMBOLS AND ACRONYMS

<table>
<thead>
<tr>
<th>Symbol/Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ANOVA</strong></td>
<td>Analysis of Variance</td>
</tr>
<tr>
<td><strong>AEP</strong></td>
<td>Anterior extreme position</td>
</tr>
<tr>
<td><strong>AP</strong></td>
<td>Anterior-Posterior</td>
</tr>
<tr>
<td><strong>bh</strong></td>
<td>Body height</td>
</tr>
<tr>
<td><strong>CAV</strong></td>
<td>constant-average-velocity</td>
</tr>
<tr>
<td><strong>COM</strong></td>
<td>Center of Mass</td>
</tr>
<tr>
<td><strong>COP</strong></td>
<td>Center of Pressure</td>
</tr>
<tr>
<td><strong>(F_{hmax})</strong></td>
<td>Predicted braking force from Eq. 2</td>
</tr>
<tr>
<td><strong>(F'_{hmax})</strong></td>
<td>Predicted braking force from Eq. 4</td>
</tr>
<tr>
<td><strong>(F_{imd}(t))</strong></td>
<td>The projection of GRF to the anterior direction of initial movement direction, (V_{\text{AEP,imd}}), Fig. 1A, Fig. 2A</td>
</tr>
<tr>
<td><strong>(F_p(t))</strong></td>
<td>The projection of GRF perpendicular to the direction of (V_{\text{AEP,imd}}) and toward turning direction to the left, Fig. 1A, Fig. 2B</td>
</tr>
<tr>
<td><strong>(F_{p_{max}})</strong></td>
<td>Peak medio-lateral GRF, (F_p(t) = F_{p_{max}} \sin(\pi t/\tau)), Fig. 1C</td>
</tr>
<tr>
<td><strong>GRF</strong></td>
<td>Ground Reaction Force</td>
</tr>
<tr>
<td><strong>I_{zz}</strong></td>
<td>Body rotational inertia</td>
</tr>
<tr>
<td><strong>imd</strong></td>
<td>initial movement direction</td>
</tr>
<tr>
<td><strong>LE</strong></td>
<td>Updated “leg effectiveness number”, (\frac{\theta_{FP} + \theta_a + \theta_{AFP}}{\theta_d})</td>
</tr>
<tr>
<td><strong>LGT</strong></td>
<td>Left Greater Trochanter</td>
</tr>
<tr>
<td><strong>M</strong></td>
<td>body mass</td>
</tr>
<tr>
<td><strong>ML</strong></td>
<td>Medio-Lateral</td>
</tr>
<tr>
<td><strong>M15%I3</strong></td>
<td>mass increased by 15% and body inertia to 3-fold</td>
</tr>
<tr>
<td><strong>M15%I3.5</strong></td>
<td>mass increased by 15% and body inertia to 3.5-fold</td>
</tr>
<tr>
<td><strong>M17%I3.5</strong></td>
<td>mass increased by 17% and body inertia to 3.5-fold</td>
</tr>
<tr>
<td><strong>M17%I4</strong></td>
<td>mass increased by 17% and body inertia to 4-fold</td>
</tr>
<tr>
<td><strong>M0%I1</strong></td>
<td>control, non-harness, NH</td>
</tr>
<tr>
<td><strong>P_{AEP,imd}</strong></td>
<td>AP foot placement relative to COM at TD</td>
</tr>
<tr>
<td><strong>(P_p)</strong></td>
<td>ML foot placement relative to COM at TD</td>
</tr>
<tr>
<td><strong>RGT</strong></td>
<td>Right Greater Trochanter</td>
</tr>
<tr>
<td><strong>std</strong></td>
<td>Standard deviation</td>
</tr>
<tr>
<td><strong>TD</strong></td>
<td>Touch Down</td>
</tr>
<tr>
<td><strong>TO</strong></td>
<td>Take Off</td>
</tr>
<tr>
<td><strong>(T_z(t))</strong></td>
<td>Free moment</td>
</tr>
<tr>
<td><strong>t</strong></td>
<td>time</td>
</tr>
<tr>
<td><strong>(V_{\text{AEP,imd}})</strong></td>
<td>Horizontal COM velocity at TD</td>
</tr>
<tr>
<td><strong>(V_f)</strong></td>
<td>Horizontal COM velocity at TO</td>
</tr>
<tr>
<td><strong>(\omega_0)</strong></td>
<td>Initial body rotational angular speed</td>
</tr>
<tr>
<td><strong>(\beta)</strong></td>
<td>Measured peak braking force, the magnitude of the half-sine component of (F_{imd}(t))</td>
</tr>
<tr>
<td><strong>(\alpha)</strong></td>
<td>Magnitude of full-sine component of (F_{imd}(t) = \alpha \sin(2\pi t/\tau) + \beta (\pi t/\tau)), Fig. 1C</td>
</tr>
</tbody>
</table>
\( \theta_\alpha \)  Body rotation angle caused by \( \alpha \sin(2\pi t/\tau) \) in \( F_{imd}(t) \), \( \frac{P_p\alpha}{2l_{zz} \pi} \tau^2 \), Appendix

Body rotation angle caused by the interaction between alpha component and

\( \theta_{\alpha F_p} \)  \( F_p(t) \), \( \frac{8F_{pmax} \tau^4 \alpha}{3\pi^4 M_{zz}} \), Appendix

\( \theta_r \)  Body rotation angle, Fig. 1A

\( \theta_d \)  COM velocity deflection angle, Fig. 1A

\( \theta_i \)  Initial angular difference between COM velocity and body orientation, Fig. 1A

Rotational angle caused by ML GRF \( F_p(t) \),

\( \theta_{F_p} \)  \( -\frac{\tau^2}{\pi^2 l_{zz}} \left( 4V_{AEP, imd} \tau + \pi^2 P_{AEP, imd} \right) F_{pmax} \), Appendix

\( \theta_f \)  The mis-match between body orientation and COM speed at TO, Fig. 1A

\( \theta_\beta \)  Rotational angle balanced by braking force, \( -\frac{P_b}{l_{zz} \pi} \tau^2 \), Appendix

\( \theta_{Tz} \)  Rotational angle caused by free moment, \( \frac{T_{max}}{l_{zz} \pi} \tau^2 \), Appendix

\( \tau \)  Stance duration

\( \varepsilon \)  Leg effectiveness number, \( \frac{\theta_{Fp}}{\theta_d} \)

\( \eta \)  Correction term to account for the effects of initial and final rotation conditions, Appendix
REFERENCES


FIGURE LEGENDS

**Figure 1.** Horizontal-plane turning model. (A) Body orientation at TD (upper) and TO (lower) during sidestep cutting turns. Coordinates are relative to the initial COM velocity at TD ($V_{AEP,imd}$). During stance the body rotates by $\theta_r$, while the COM deflects by $\theta_d$. At TD there is pre-rotation between body orientation and COM velocity ($\theta_i$). Positive $\theta_i$ indicates that body rotation precedes COM velocity direction while negative indicates lag, and the case where $\theta_d = \theta_i + \theta_r + \theta_f$ is pictured. (B) Harness used to change body rotational inertia ($I_{zz}$). (C) Horizontal plane human turning model with body posture at TD and TO. AP force, $F_{imd}(t)$, is approximated by the combination of a full sine wave (alpha component) and a half sine wave (beta component, most commonly a braking force). ML force, $F_p(t)$, is approximated by another half sine wave with peak $F_{pmax}$. Free moment, $T_z(t)$, is fitted by a half sine wave with peak $T_{max}$. In the current figure, $T_z(t)$ is negative and against turning direction. The body posture in (C) was first averaged across all trials within $M0\%I1$, and then averaged across all rotational inertia levels and participants.

**Figure 2.** Force and COM speed profile ensembles for different rotational inertias for the stance phase of the turning step. $F_{imd}$ (A) and $F_p$ (B) are the GRF projection along and perpendicular to initial COM velocity at TD ($V_{AEP,imd}$). COM speed in the horizontal plane (C) first decreased and then increased back to the original value. Different rotational inertias are represented by different line types, $M0\%I1$ solid, $M15\%I3$ dashed, $M15\%I3.5$ dashed and dotted, $M17\%I3.5$ dotted, and $M17\%I4$ solid gray and cross. Each line is the ensemble average of all trials within the same rotational inertia for the same participant, and then averaged across participants.

**Figure 3.** The effects of rotational inertia on average predicted and measured peak braking forces (A). Negative values indicate deceleration in initial COM velocity direction, $V_{AEP,imd}$, and positive values indicate acceleration. $F_{hmax}$ (black solid) is the braking force predicted from the original model (Eq. 2); $\beta$ (red dashed) is the measured peak braking force; $F'_{hmax}$ (blue dash and dotted ) is the predicted braking force from the revised model, as expressed in Eq. 4. (B) Averaged net AP impulse (mean±std) for different inertia conditions.

**Figure 4.** Ground-reaction forces relative to the body in different inertia conditions. Body posture and GRF are shown at 50% of stance phase during all (A) TURN and (B) RUN tasks. (C) The definition of the angle between GRF and virtual leg connecting COM and COP at 50% of stance, and it was not significantly influenced by either task ($p_A = 0.9$) or rotational inertia ($p_B = 0.2$). Data represent averages of all replicate trials within each rotational inertia conditions, in turn averaged across all participants. The COM in (A) or (B) represents the overall calculated COM position for human and harness together. The views from (A) and (B) are from the back: the participant is running into the paper with the right foot in stance.

**Figure 5.** Opposing contributions of different factors to body rotation during turns with
different rotational inertias (mean±std). (A) COM deflection ($\theta_d$) compared to the two components of body rotation: pre-rotation ($\theta_i$) and body rotational angle ($\theta_r$). (B) Body rotation ($\theta_r$) and its components caused by ML GRF ($\theta_{Fp}$), initial body rotational angular speed ($\omega_0\tau$), braking force ($\theta_{\beta}$), free moment ($\theta_{Tz}$), alpha component in $F_{imd}$ ($\theta_\alpha$), the interaction between alpha component and $F_p$ ($\theta_{\alpha Fp}$).

**Figure 6.** Relationships between measured, $\beta$, and predicted peak braking force. (A) $F_{\text{hmax}}$ from the original turning model as expressed by Eq. 2, (B) $F'_\text{hmax}$ from Eq. 4. Different rotational inertias are of different colors, $M0\%I1$ black, $M15\%I3$ red, $M15\%I3.5$ blue, $M17\%I3.5$ magenta, and $M17\%I4$ green, and each symbol represents an individual participant.

**Figure 7.** (A) The relationship between COM speed at TO ($V_f$) and TD ($V_{AEP,imd}$). (B) Peak braking force necessary to maintain COM speed at TO the same as at TD. The definitions of symbols follow Fig. 6.
Table 1. Values for turning parameters for different rotational inertia TURN tasks

<table>
<thead>
<tr>
<th>Symbol (Units)</th>
<th>p value</th>
<th>M0%I1&lt;sup&gt;(I)&lt;/sup&gt;</th>
<th>M15%I3&lt;sup&gt;(II)&lt;/sup&gt;</th>
<th>M15%I3.5&lt;sup&gt;(III)&lt;/sup&gt;</th>
<th>M17%I3.5&lt;sup&gt;(IV)&lt;/sup&gt;</th>
<th>M17%I4&lt;sup&gt;(V)&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>TD speed, V&lt;sub&gt;AEP,imd&lt;/sub&gt; (m/s)</td>
<td>0.32</td>
<td>2.9±0.2</td>
<td>2.7±0.2</td>
<td>2.8±0.2</td>
<td>2.8±0.3</td>
<td>2.7±0.2</td>
</tr>
<tr>
<td>TO speed, V&lt;sub&gt;f&lt;/sub&gt; (m/s)</td>
<td>0.67</td>
<td>2.9±0.3</td>
<td>2.7±0.2</td>
<td>2.7±0.2</td>
<td>2.8±0.2</td>
<td>2.8±0.2</td>
</tr>
<tr>
<td>COM velocity deflection, θ&lt;sub&gt;d&lt;/sub&gt; (°)</td>
<td>0.50</td>
<td>27±4</td>
<td>25±6</td>
<td>25±3</td>
<td>25±4</td>
<td>25±5</td>
</tr>
<tr>
<td>Body rotation, θ&lt;sub&gt;b&lt;/sub&gt; (°)</td>
<td>0.98</td>
<td>13±7</td>
<td>13±6</td>
<td>13±3</td>
<td>12±3</td>
<td>12±3</td>
</tr>
<tr>
<td>Leg effectiveness # ε</td>
<td>&lt; 0.01</td>
<td>3.1±0.8&lt;sup&gt;III,IV,V&lt;/sup&gt;</td>
<td>1.4±1.2</td>
<td>1.0±0.3&lt;sup&gt;V&lt;/sup&gt;</td>
<td>0.8±0.6</td>
<td>0.6±0.4</td>
</tr>
<tr>
<td>Predicted peak braking force, F&lt;sub&gt;Hmax&lt;/sub&gt; (N)</td>
<td>&lt; 0.01</td>
<td>-140±41&lt;sup&gt;III,IV,V&lt;/sup&gt;</td>
<td>-27±95</td>
<td>-1.9±51&lt;sup&gt;V&lt;/sup&gt;</td>
<td>31±100</td>
<td>74±72</td>
</tr>
<tr>
<td>Measured peak braking force, β (N)</td>
<td>0.08</td>
<td>-130±36</td>
<td>-88±88</td>
<td>-100±37</td>
<td>-77±84</td>
<td>-68±99</td>
</tr>
<tr>
<td>AP foot placement, P&lt;sub&gt;AEP,imd&lt;/sub&gt; (m)</td>
<td>&lt; 0.05</td>
<td>0.248±0.024&lt;sup&gt;II&lt;/sup&gt;</td>
<td>0.211±0.017</td>
<td>0.224±0.015</td>
<td>0.229±0.031</td>
<td>0.220±0.026</td>
</tr>
<tr>
<td>ML foot placement, P&lt;sub&gt;p&lt;/sub&gt; (m)</td>
<td>0.05</td>
<td>65±37</td>
<td>33±11</td>
<td>40±6.7</td>
<td>43±10</td>
<td>38±8.7</td>
</tr>
<tr>
<td>Initial angular rotation speed, ω&lt;sub&gt;0&lt;/sub&gt; (°/s)</td>
<td>&lt; 0.05</td>
<td>0.275±0.026&lt;sup&gt;II&lt;/sup&gt;</td>
<td>0.320±0.023</td>
<td>0.310±0.018</td>
<td>0.303±0.026</td>
<td>0.310±0.025</td>
</tr>
<tr>
<td>Stance duration, τ (s)</td>
<td>&lt; 0.01</td>
<td>18±10</td>
<td>11±3</td>
<td>12±2</td>
<td>13±4</td>
<td>12±3</td>
</tr>
<tr>
<td>Angle caused by ω&lt;sub&gt;0&lt;/sub&gt;, ω&lt;sub&gt;0&lt;/sub&gt;τ (°)</td>
<td>0.17</td>
<td>8±9</td>
<td>3±5</td>
<td>4±5</td>
<td>6±6</td>
<td>3±5</td>
</tr>
<tr>
<td>Initial pre-rotation, θ&lt;sub&gt;i&lt;/sub&gt; (°)</td>
<td>0.36</td>
<td>4±5</td>
<td>10±2</td>
<td>8±4</td>
<td>6±5</td>
<td>10±4</td>
</tr>
<tr>
<td>Final rotation mismatch, θ&lt;sub&gt;f&lt;/sub&gt; (°)</td>
<td>0.10</td>
<td>-42±6&lt;sup&gt;III,IV,V&lt;/sup&gt;</td>
<td>-23±16</td>
<td>-14±1&lt;sup&gt;V&lt;/sup&gt;</td>
<td>-14±3</td>
<td>-12±2</td>
</tr>
<tr>
<td>Angle caused by full-sine component of F&lt;sub&gt;imd&lt;/sub&gt;(t), θ&lt;sub&gt;α&lt;/sub&gt; (°)</td>
<td>&lt; 0.01</td>
<td>17±4&lt;sup&gt;III,IV,V&lt;/sup&gt;</td>
<td>11±9</td>
<td>7±1</td>
<td>6±2</td>
<td>6±2</td>
</tr>
<tr>
<td>Angle caused by interaction, θ&lt;sub&gt;αβγ&lt;/sub&gt; (°)</td>
<td>&lt; 0.05</td>
<td>-8±8&lt;sup&gt;II&lt;/sup&gt;</td>
<td>1±4</td>
<td>0±4</td>
<td>-1±3</td>
<td>0±3</td>
</tr>
</tbody>
</table>

mean±std. Significant difference in post-hoc comparisons are indicated by superscript (p < 0.0051). For all angles, positive value is along the turning direction.
**Table 2. Values for turning parameters for different rotational inertia RUN tasks**

<table>
<thead>
<tr>
<th>Symbol (Units)</th>
<th>p value</th>
<th>M0%I1(I)</th>
<th>M15%I3(II)</th>
<th>M15%I3.5(III)</th>
<th>M17%I3.5(IV)</th>
<th>M17%I4(V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TD speed $V_{AEP,imd}$ (m/s)</td>
<td>0.26</td>
<td>3.2±0.2</td>
<td>3.0±0.2</td>
<td>3.0±0.2</td>
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<td>3.1±0.2</td>
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<tr>
<td>TO speed $V_f$ (m/s)</td>
<td>&lt; 0.01</td>
<td>3.2±0.2</td>
<td>3.0±0.2</td>
<td>3.0±0.2</td>
<td>3.1±0.3</td>
<td>3.0±0.2</td>
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<td>COM velocity deflection $\theta_d$ (°)</td>
<td>0.38</td>
<td>0±1</td>
<td>1±1</td>
<td>0±1</td>
<td>0±1</td>
<td>0±1</td>
</tr>
<tr>
<td>Body rotation $\theta_r$ (°)</td>
<td>&lt; 0.01</td>
<td>-10±4</td>
<td>-8±5</td>
<td>-4±4</td>
<td>-7±3</td>
<td>-4±2</td>
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<tr>
<td>Leg effectiveness # $\varepsilon$</td>
<td>0.25</td>
<td>-0.3±3.0</td>
<td>1.6±1.3</td>
<td>0.5±0.9</td>
<td>0.6±0.8</td>
<td>0.4±0.9</td>
</tr>
<tr>
<td>AP foot placement $P_{AEP,imd}$ (m)</td>
<td>0.06</td>
<td>-0.321±0.085</td>
<td>-0.441±0.040</td>
<td>-0.399±0.065</td>
<td>-0.407±0.074</td>
<td>-0.404±0.084</td>
</tr>
<tr>
<td>ML foot placement $P_p$ (m)</td>
<td>0.24</td>
<td>0.058±0.030</td>
<td>0.071±0.033</td>
<td>0.060±0.024</td>
<td>0.053±0.026</td>
<td>0.052±0.035</td>
</tr>
<tr>
<td>Initial angular rotation speed $\omega_0$ (°/s)</td>
<td>&lt; 0.05</td>
<td>-25±7</td>
<td>-26±18</td>
<td>-12±14</td>
<td>-27±12</td>
<td>-13±5</td>
</tr>
<tr>
<td>Stance duration $\tau$ (s)</td>
<td>&lt; 0.05</td>
<td>0.248±0.022 (II,III,V)</td>
<td>0.299±0.028</td>
<td>0.293±0.017</td>
<td>0.287±0.022</td>
<td>0.297±0.024</td>
</tr>
<tr>
<td>Angle caused by $\omega_0$ $\omega_0 \tau$ (°)</td>
<td>&lt; 0.05</td>
<td>-6±2</td>
<td>-8±6</td>
<td>-3±4</td>
<td>-8±3</td>
<td>-4±2</td>
</tr>
<tr>
<td>Initial pre-rotation $\theta_i$ (°)</td>
<td>0.37</td>
<td>3±4</td>
<td>4±4</td>
<td>0±4</td>
<td>0±7</td>
<td>1±4</td>
</tr>
<tr>
<td>Final rotation mismatch $\theta_f$ (°)</td>
<td>0.68</td>
<td>7±4</td>
<td>5±7</td>
<td>3±5</td>
<td>6±6</td>
<td>4±6</td>
</tr>
</tbody>
</table>

Mean±std. Significant difference in post-hoc comparisons are indicated by superscript ($p < 0.0051$). For all angles, positive value is along the turning direction as in Table 1.
Appendix

Relaxing the assumptions of constant speed and zero rotational initial conditions requires a re-derivation of the turning model. Assuming the AP direction GRF, $F_{imd}$, is given by (A.1), then AP direction speed during turning is a function of time (A.2).

$$F_{imd}(t) = a \sin \frac{2\pi t}{\tau} + b \sin \frac{\pi t}{\tau}$$ (A.1)

$$V_{imd}(t) = -\frac{\tau}{\pi M} \left[ a \left( \cos \frac{2\pi t}{\tau} - 1 \right) + b \left( \cos \frac{\pi t}{\tau} - 1 \right) \right] + V_{AEP,imd}$$ (A.2)

Integrate $V_{imd}(t)$ with respect to time results in AP direction COM displacement (A.3).

$$x_{imd}(t) = -\frac{t^2}{\pi^2 M} \left( \alpha \sin \frac{2\pi t}{\tau} + \beta \sin \frac{\pi t}{\tau} \right) + \left( V_{AEP,imd} + \frac{\alpha + \beta}{2 \pi M} \right) t + P_{AEP,imd}$$ (A.3)

The projection of GRF along the ML direction is approximated by (A.4).

$$F_p(t) = F_{pmax} \sin \frac{\pi t}{\tau}$$ (A.4)

According to the definition, the COM velocity at TD is perpendicular to the ML direction.

The COM speed along ML direction as a function to time is therefore given in (A.5).

$$V_p(t) = \frac{F_{pmax}}{\pi M} \left( 1 - \cos \frac{\pi t}{\tau} \right)$$ (A.5)

Integrating with respect to time results in the COM displacement in ML direction (A.6).

$$x_p(t) = -\frac{F_{pmax}}{M} \left( \frac{1}{\pi} \right)^2 \sin \frac{\pi t}{\tau} + \frac{F_{pmax}}{\pi M} t + P_p$$ (A.6)

Free moment is approximated by a half sine wave in stance phase (A.7).

$$T_z(t) = T_{max} \sin \frac{\pi t}{\tau}$$ (A.7)

Hence, the net moment applying to COM in stance phase is (A.8).

$$T(t) = x_p(t) F_{imd}(t) - x_{imd}(t) F_p(t) + T_z(t)$$ (A.8)

Integrating with respect to time results in the angular speed in stance phase (A.9).

$$\dot{\theta}(t) = \omega_0 - \frac{1}{l_z \pi} \left[ F_{pmax} \left( V_{AEP,imd} + \frac{\alpha}{2 \pi M} \right) \left( \frac{\pi}{\tau} \sin \frac{\pi t}{\tau} - t \cos \frac{\pi t}{\tau} \right) + 2 \left( \sin \frac{\pi t}{2 \tau} \right)^2 \left( -T_{max} - P_p \beta + F_{pmax} P_{AEP,imd} - P_p \alpha \left( \sin \frac{\pi t}{\tau} \right)^2 - F_{pmax} \frac{\alpha}{2 \pi} \right) - \frac{1}{2 \pi} \left( \frac{\pi}{\tau} \right)^2 \left( \sin \frac{\pi t}{\tau} \right)^3 + \sin \frac{\pi t}{\tau} \cos \frac{\pi t}{\tau} - t \pi \cos \frac{2\pi t}{\tau} \right]$$ (A.9)

Finally, integrating $\dot{\theta}(t)$ during the stance phase results in the angular displacement by the
end of turning at TO (A.10).

$$\theta_r(\tau) = \int_0^\tau \left( \int_0^\tau \frac{T(\lambda)}{I_{zz}} d\lambda \right) dt + \int_0^\tau \omega_0 dt$$

$$= -\frac{\tau^2}{\pi^3 I_{zz}} \left( 4V_{AEP,imd} \tau + \pi^2 P_{AEP,imd} \right) F_{p_{\text{max}}} + \frac{P_{pF}}{2I_{zz} \pi} \tau^2 - \frac{8F_{p_{\text{max}}} \tau^4 \alpha}{3 \pi^4 M_{Izz}} + \frac{F_{p \alpha}}{2I_{zz} \pi} \tau^2 + \frac{T_{\text{max}}}{I_{zz} \pi} \tau^2 + \omega_0 \tau$$

(A.10)

The first component of the right side of equal sign in (A.10), $-\frac{\tau^2}{\pi^3 I_{zz}} \left( 4V_{AEP,imd} \tau + \pi^2 P_{AEP,imd} \right) F_{p_{\text{max}}}$ represents rotation due to $F_p$, and can be abbreviated $\theta_{FP}$. The second component, $\frac{P_{pF}}{2I_{zz} \pi} \tau^2$, is the rotational angle caused by braking force along turning direction, and can be abbreviated $\theta_\beta$. The third component, $-\frac{8F_{p_{\text{max}}} \tau^4 \alpha}{3 \pi^4 M_{Izz}}$, is the angle caused by the interaction between alpha component and $F_p(t)$, and can be abbreviated $\theta_{aFP}$. The fourth component, $\frac{F_{p \alpha}}{2I_{zz} \pi} \tau^2$, is the angle caused by the alpha component of $F_{imd}(t)$, and can be abbreviated $\theta_{aFP}$. The fifth component, $\frac{T_{\text{max}}}{I_{zz} \pi} \tau^2$, is the angle caused by free moment, and can be abbreviated $\theta_{Tz}$. The last component represents the contribution of initial rotational velocity. All of these components are angles, and can be summarized as

$$\theta_r = \theta_{FP} + \theta_\beta + \theta_{aFP} + \theta_{aFP} + \theta_{Tz} + \omega_0 \tau$$

(A.11)

In this study, we found that humans do not precisely match deflection with body rotation, but instead begin and end turns at initial and final body angles relative to movement deflection (Fig. 1A). Separating these contributors yields a final relationship:

$$\theta_d = \theta_r + \theta_i + \theta_f$$

(A.12)

Substituting A.12 into A.11 and rearranging as contributions to braking, $\theta_\beta$, yields

$$-\theta_\beta = -\theta_d + \theta_{FP} + \theta_{aFP} + \theta_{aFP} + \theta_{Tz} + \omega_0 \tau + \theta_i + \theta_f$$

(A.13)

Substituting $\frac{P_{pF}}{2I_{zz} \pi} \tau^2$ for $\theta_\beta$ and multiplying both sides by -1 results in
\[
\frac{P_\beta}{I_{xx} \pi} \tau^2 = \theta_d - \theta_{FP} - \theta_{aFP} - \theta_{\alpha} - \theta_{Tz} - \omega_0 \tau - \theta_i - \theta_f
\]  \hspace{1cm} (A.14)

Dividing A.14 by \( \theta_d \) results in
\[
\frac{P_\beta}{I_{xx} \pi \theta_d^2} \tau^2 = 1 - \frac{\theta_{FP} + \theta_{aFP} + \theta_a}{\theta_d} - \frac{\omega_0 \tau + \theta_i + \theta_f}{\theta_d} - \frac{\theta_{Tz}}{\theta_d}
\]  \hspace{1cm} (A.15)

Substituting \( LE = \frac{\theta_{FP} + \theta_a + \theta_{aFP}}{\theta_d} \), and \( \eta = \frac{\omega_0 \tau + \theta_i + \theta_f}{\theta_d} \) into A.15, allows the braking force to be predicted from
\[
F'_{hm_{ax}} = \frac{\pi I_{xx} \theta_d}{\tau^2 P_\beta} \left( 1 - LE - \eta - \frac{\theta_{Tz}}{\theta_d} \right).
\]  \hspace{1cm} (A.16)

We found free moments to be relatively small and not make a substantial contribution to running turns. Ignoring the free moment results in
\[
F'_{hm_{ax}} = \frac{\pi I_{xx} \theta_d}{\tau^2 P_\beta} \left( 1 - LE - \eta \right)
\]  \hspace{1cm} (A.17)

which is the final format of Eq. 4. It should be noted that using these equations express relationships among parameters only, and could be used to predict the value of any parameter based on measured or estimated values for others. Braking forces were chosen for prediction because they are observed during turning but not constant-average-velocity running, have a large variance, and could potentially be modulated during a step to control body rotation. However, this does not imply that braking forces do not have other functions (such as maintaining constant velocity), or that other parameters (such as foot placement) are not actively controlled during maneuvers.