Generalizing Stepping Concepts To Non-Straight Walking

Jonathan B. Dingwell [1,*], Anna C. Render [1], David M. Desmet [1], Joseph P. Cusumano [2]

[1] Department of Kinesiology, Pennsylvania State University, University Park, Pennsylvania, United States of America

[2] Department of Engineering Science & Mechanics, Pennsylvania State University, University Park, Pennsylvania, United States of America

* Corresponding Author:

Email: dingwell@psu.edu Web: https://sites.psu.edu/dingwell/

CRediT Author Statement

Jonathan B. Dingwell: Conceptualization, Methodology, Software, Validation, Formal Analysis, Resources, Data Curation, Writing – Original Draft, Writing – Review & Editing, Visualization, Supervision, Project Administration, Funding Acquisition
Anna C. Render: Conceptualization, Methodology, Validation, Writing – Review & Editing, Visualization, Project Administration
David M. Desmet: Conceptualization, Methodology, Validation, Writing – Review & Editing, Visualization
Joseph P. Cusumano: Conceptualization, Methodology, Writing – Review & Editing, Supervision, Funding Acquisition

Declaration of Competing Interest

The authors declare that there are no conflicts of interest associated with this work.

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Abstract
People rarely walk in straight lines. Instead, we make frequent turns or other maneuvers. Spatiotemporal parameters fundamentally characterize gait. For straight walking, these parameters are well-defined for that task of walking on a straight *path*. Generalizing these concepts to *non*-straight walking, however, is not straightforward. People also follow non-straight paths imposed by their environment (store aisle, sidewalk, etc.) or choose readily-predictable, stereotypical paths of their own. People actively maintain lateral position to stay on their path and readily adapt their stepping when their path changes. We therefore propose a conceptually coherent convention that defines step lengths and widths relative to known walking paths. Our convention simply re-aligns lab-based coordinates to be tangent to a walker's path at the mid-point between the two footsteps that define each step. We hypothesized this would yield results both more *correct* and more consistent with notions from straight walking. We defined several common non-straight walking tasks: single turns, lateral lane changes, walking on circular paths, and walking on arbitrary curvilinear paths. For each, we simulated idealized step sequences denoting "perfect" performance with known constant step lengths and widths. We compared results to path-independent alternatives. For each, we directly quantified accuracy relative to known *true* values. Results strongly confirmed our hypothesis. Our convention returned vastly smaller errors and introduced *no* artificial stepping asymmetries across all tasks. All results for our convention rationally generalized concepts from straight walking. Taking walking paths explicitly into account as important task goals themselves thus resolves conceptual ambiguities of prior approaches.

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1. Introduction

When we walk in the real world, we rarely walk in straight lines. We frequently turn and/or make other maneuvers (Glaister et al., 2007), starting from when we first learn to walk (Adolph et al., 2012). As adults, we skillfully modulate foot placements (Bruijn and van Dieën, 2018) to maneuver (Acasio et al., 2017; Desmet et al., 2022). But as we get older, we are less able to shift our weight effectively (Ambrose et al., 2013), which can induce falls and serious injury (Burns and Kakara, 2018). Older adults fall most often while walking (Kelsey et al., 2012) and frequently while attempting non-straight walking tasks or maneuvers (Robinovitch et al., 2013).

Spatiotemporal gait parameters (step length, width, time, etc.) fundamentally characterize gait. People modify them regularly in real environments (Twardzik et al., 2019) and they can predict consequences like fall risk (Taylor et al., 2013). Spatiotemporal parameters are well-defined for straight walking (Whittle, 2007), where most gait labs presume a constant forward direction of progression (DoP). Here, step lengths and widths are rightly defined relative to the *task* of walking on that straight path. However, generalizing these concepts to *non*-straight walking is not straightforward. Given the need to predict and/or prevent falls that often occur during complex tasks (Robinovitch et al., 2013) and increasing emphasis on real-world walking (Bergsma et al., 2021; Glaister et al., 2007), we must reassess what these biomechanical quantities mean for non-straight walking.

Some have proposed defining DoP from anatomically-based local coordinates, like those defined by center-of-mass (CoM) trajectories (Ho et al., 2023), or horizontal pelvis (Ho et al., 2023; Kainz et al., 2016) or trunk (Jansen et al., 2011) rotations. Unfortunately, these are decidedly problematic. Even for straight walking, the CoM continuously oscillates side-to-side (Saunders et al., 1953; Tesio et al., 2010), the pelvis continuously rotates (Lewis et al., 2017; Saunders et al., 1953), and the trunk rotates separately from the pelvis (Prins et al., 2019). Thus, these approaches necessarily yield *many* possible (but arbitrary) DoPs that only rarely align with the true DoP (see Supplement). Such difficulties make clear this is not about merely finding the right "method", but a fundamental question of how we conceive of these quantities beforehand.

An alternative based only on step placements was proposed by Huxham et al. (2006), extending Courtine & Schieppati (2003). Huxham calculates step lengths and widths from a DoP defined by a line connecting consecutive

ipsilateral foot placements. This convention has been applied to executing turns in one step (He et al., 2018; Huxham et al., 2006) or over multiple steps (Bergsma et al., 2021; Conradsson et al., 2018; Courtine and Schieppati, 2003; Dixon et al., 2013; Tillman et al., 2022), to walking around circular (Ho et al., 2023; Xu et al., 2017) or other non-straight (Bland et al., 2019; Fino et al., 2016) paths, even walking outdoors (Bergsma et al., 2021). However, Huxham's convention produces several counter-intuitive consequences. First, consecutive step lengths are measured along different DoP (see their Fig. 1B). Hence, adding consecutive step lengths will not equal the corresponding stride length, inconsistent with definitions from straight walking. Second, Huxham's convention exaggerates distinctions between so-called "step turn" steps (where the stepping foot steps away from the stance foot) and "spin turn" steps (where the stepping foot steps towards/across the stance foot) (Hase and Stein, 1999). While seemingly relevant for single-step turns, when people turn over multiple steps, they necessarily alternate "step turn" steps with "spin turn" steps, making the idea of differentiating these as distinct "strategies" (Conradsson et al., 2018; Dixon et al., 2013) somewhat illogical. Even for straight walking, people step slightly away from or towards/across their stance foot at every step, again making Huxham's convention inconsistent with conventional definitions. Third, not all non-straight walking involves turns, as sometimes we step sideways to make lateral maneuvers (Acasio et al., 2017; Desmet et al., 2022). It is not clear if Huxham's convention can even be meaningfully applied to such tasks.

It is important to view stepping (and hence, walking) as not merely something to be "measured", but the product of a *task* one performs. The prior efforts above, however, did not consider that people walk intentionally (Gordon et al., 2021) to achieve specific goal(s) (Cusumano and Cesari, 2006). People follow *paths* (hallways, store aisles, sidewalks, etc.) when they walk (Dingwell and Cusumano, 2019). When their environment does not impose an explicit path, people choose their own (Moussaïd et al., 2011). Indeed, these paths are stereotypical (Hicheur et al., 2007) and well-predicted by conventional control laws (Arechavaleta et al., 2008; Brown et al., 2021; Pham et al., 2007). People then balance maintaining step width with their lateral position relative to their path, so they do not drift sideways off their path (Dingwell and Cusumano, 2019). They readily modulate how they regulate their steps if given explicit feedback (Render et al., 2021), or to make lateral maneuvers (Desmet et al., 2022). Conversely, neither Huxham's convention nor the anatomically-based approaches described above reference the path followed or any other goal(s) to maintain. The logic of those approaches thus seems backwards: tasks are not created by where people step – instead, people choose where to step to accomplish particular task goals (including to follow some path). Because stepping behavior is well-explained by regulation processes that minimize errors with respect to specific task goals (Desmet et al., 2022; Dingwell and Cusumano, 2019; Dingwell et al., 2010), stepping parameters (step length, width, etc.) should be defined consistently with these processes.

Referencing stepping parameters to the walking path/trajectory directly generalizes original stepping notions from straight walking (Whittle, 2007) and also respects the nature of intrinsic motor regulation. As such, we hypothesize this will yield more *accurate* results. We first propose a convention for defining step lengths and widths relative to a known path. We compare our proposed approach to that of Huxham et al. (2006). To determine any measure's *accuracy*, one must compare to known true values. This is not possible with experimental data, as one can never know what the "correct" values are. We therefore instead simulated idealized step sequences to constitute "perfect" performance in several non-straight walking tasks. We show our proposed approach fully disambiguates "steps" from "strides", yields more accurate measures that are far more consistent with straight walking definitions, applies across multiple non-straight tasks, and accommodates primary stepping goals people try to maintain as they walk.

2. Methods

2.1 Stepping Parameters for Non-Straight Walking:

The challenge is to define step lengths and widths relative to some direction of forward progression (DoP) that may change at each step (Huxham et al., 2006). The convention proposed by Huxham et al. (2006) defines a DoP for each *stride* as the line connecting the two ipsilateral heel strikes that form that stride (Fig. 1A). "Stride width" (w_H) is

measured perpendicular to this line. Step length (l_H) is measured from the resulting intersection to the heel of the leading foot (Fig. 1A). These measurements make no reference to any path the person walks on or follows.

[Insert Figure 1 About Here]

However, people do not "just walk" – they walk intentionally (Gordon et al., 2021) in goal-directed ways (Cusumano and Cesari, 2006). As such, they follow paths to reach their destinations (Arechavaleta et al., 2008; Moussaïd et al., 2011). Given any such path, here we define each individual step from only its two consecutive foot placements (Fig. 1B). We take body position for that step as the mid-point between them (Dingwell and Cusumano, 2019). This can serve as a discrete (once per step) proxy for CoM location (Desmet et al., 2022; Orendurff et al., 2004), but has the virtue of being determined entirely from step positions. Then, just as one would transform local coordinate systems between body segments (foot-to-shank, shank-to-thigh, etc.), we merely rotate the global coordinate system, $[x,z]$, to be tangent to the path at the point nearest to the body position ($[x',z']$; Fig. 1B). We then calculate step widths (w_P) and lengths (l_P) as usual (Whittle, 2007), only now in path-aligned $[x',z']$ coordinates (Fig. 1B). We define foot placements ($[x'_L,z'_L]$ and $[x'_R,z'_R]$) relative to the relevant tangent point on the path. Step length is the distance in $+x'$ from trailing to leading foot. Step width is the lateral displacement between the right and left feet: $w = z'_R - z'_L$ (i.e., so cross-over steps yield negative w). We additionally define lateral body position relative to the path (Dingwell and Cusumano, 2019) (not analyzed here) as the locally-lateral midpoint between the feet: $z'_B = ½(z'_L + z'_R)$.

2.2 Non-Straight Walking Tasks:

We defined several non-straight walking tasks humans commonly perform: make a *Single Turn* (as though turning a corner), make a *Lateral Lane Change* (such as to avoid an obstacle), walk around a *Circular Path* (as though going around a curve), and walk along an *Arbitrary Curvilinear Path* (such as a winding garden path). For all tasks, we assumed a global (i.e., lab) coordinate system as $[x,z]$ in the horizontal plane to be $+x$ "forward" (left-to-right in figures) and $+z$ to the walker's right (down in figures).

For each task, we simulated idealized step sequences that constituted "perfect" performance (i.e., zero error) in that task. We constructed step sequences with all steps having the same pre-defined step length (L = 0.60m) and step width (W = 0.15m). While these values are typical (Herssens et al., 2020), our findings and conclusions do not depend on any specific choice(s) of L and/or W.

For *Single Turns*, we defined a path to run straight along the $+x$-axis, then (instantaneously) turn by angle Θ_{Turn} at the origin ([0,0]), then continue straight again in the new direction. We derived, as geometric functions of L, W, and Θ_{Turn}, where to place each foot so every step had length L and width W and was located exactly $\pm W/2$ to either side of the path. Hence, the walker walks with exactly L and W up to the turn step, turns the full Θ_{Turn} at that foot placement, then continues walking with exactly L and W in the new (turned) direction. We present results here for $\Theta_{\text{Turn}} \in \{-30°, -75°, +60°\}$.

For *Lateral Lane Change* maneuvers, we defined a path to run straight along the $+x$-axis, with a lateral shift of displacement Δz occurring just after the origin ([0,0]), and then continuing straight in the $+x$ direction after the lane-change. We derived, as functions of L, W, and Δz, where to place each foot so every step had length L and width W and was exactly $\pm W/2$ to either side of the path. Here, the walker walks with steps of exactly L and W up to the origin, fully changes lanes on the next foot placement, then continues walking with exactly L and W thereafter. We present results here for $\Delta z \in \{+30\text{cm}, +60\text{cm}, -45\text{cm}\}$ (or in terms of step widths: $\Delta z \in \{+2, +4, -3\} \cdot W$).

For walking around *Circular Paths*, we defined each path as a circle centered at the origin with radius R_{Path}. We placed each alternating footstep along the path at consecutive distances L, measured along the arc of the circle, and with alternating feet placed at radial distances $R_{Path} \pm W/2$ perpendicular to the circular path. Here, we took these footstep sequences to denote walking counter-clockwise around each circle. However, the exact same footsteps could

equally represent clockwise walking. We present results here for individual paths of $R_{Path} \in \{6.0\text{m}, 1.5\text{m}, 0.75\text{m}\}$ and also across the range of $0.5\text{m} \leq R_{Path} \leq 10.0\text{m}$.

For walking along an *Arbitrary Curvilinear Path*, we defined a path as a 5th order polynomial:

$$z = -A \cdot \left[(x-6) \cdot (x+6) \cdot (x^3 - 4x) \right] = -Ax^5 + 40Ax^3 - 144Ax, \quad (1)$$

on the interval $x \in [-6\text{m}, +6\text{m}]$ and with amplitude $A = 0.0025\text{m}$. This yielded a path that was symmetrical about the origin, started and ended on the $+x$-axis, and had two larger peaks (minimum radius-of-curvature (i.e., instantaneous R_{Path}) ≈ 0.61m) and two smaller peaks (minimum radius-of-curvature ≈ 1.6m). The shape and curvature range of this path are typical of real paths (Arechavaleta et al., 2008; Rudenko et al., 2020). We placed each alternating footstep at consecutive distances L measured along the polynomial, and with alternating feet placed at distances $\pm W/2$ perpendicular to the path at each foot placement. This yielded a sequence of 32 consecutive footsteps along this path.

2.3 Data Analyses

For all steps in each simulated task, we used Huxham's convention (Fig. 1A) to compute step lengths (l_H) and stride widths (w_H). We used our proposed convention (Fig. 1B) to compute step lengths (l_P) and widths (w_P). To quantify the *accuracy* of each measurement, we scaled each computed value to the pre-defined *true* values, L and W: any value $\{l_H, l_P\} \neq L$ or $\{w_H, w_P\} \neq W$ indicated an error. We also calculated percent errors (%Error) in each step measure as:

$$\%\text{Error} = \left(\frac{Calculated - True}{True} \right) \times 100\%. \quad (2)$$

For circular paths, we computed and plotted %Errors of all measures across the range of $0.5\text{m} \leq R_{Path} \leq 10.0\text{m}$ for both "outside-to-inside" and "inside-to-outside" steps. We computed a Universal Symmetry Index (*USI*) (Alves et al., 2020) between these outside-to-inside ("χ_{oi}") and inside-to-outside ("χ_{io}") steps as:

$$USI = \frac{(\chi_{oi} - \chi_{io})}{\sqrt{2 \cdot (\chi_{oi}^2 + \chi_{io}^2)}} \times 100\%, \quad (3)$$

where $\chi \in \{l_H, l_P, w_H, w_P\}$. For $\{\chi_{oi}, \chi_{io}\}$ that can have either positive or negative values, Eq. (3) returns $USI = 0$ for perfect symmetry ($\chi_{oi} = \chi_{io}$), with a bounded maximal range of $USI \in [-100\%, +100\%]$ otherwise (Alves et al., 2020). Because we simulated perfectly aligned steps along each circular path, step lengths and widths should likewise be perfectly symmetrical: i.e., one should obtain the same results for all steps, whether walking clockwise or counter-clockwise around the circle.

Unlike for straight paths, setting $[x', z']$ at different locations along any *curved* path will alter resulting step widths and step lengths calculated, potentially introducing (artificial) asymmetries (Fig. 2). Here, we directly quantified these effects for our proposed convention. We computed l_P and w_P across the range of possible $[x', z']$ from the trailing (rear) foot placement (Fig. 2A) to the leading (front) foot placement (Fig. 2B) for circular paths of $R_{Path} \in \{6.0\text{m}, 1.5\text{m}, 0.75\text{m}\}$. At each $[x', z']$, we computed %Errors in both step length and width for both outside-to-inside and inside-to-outside steps and *USI* values (Eq. 3) between them.

[Insert Figure 2 About Here]

For the arbitrary curvilinear path, we computed %Errors for both measures at each step and plotted these versus the x axis location of each corresponding step.

3. Results

For *Single Turns* (Fig. 3), both conventions yielded perfect performance ($\{l_H, l_P\} = L$; $\{w_H, w_P\} = W$) for the straight sections of all paths (not marked on figure). For the turn step itself, however, Huxham's convention (Fig. 3A) yielded substantial errors in step length (l_H: $-36\% \leq \%\text{Errors} \leq -1\%$) and especially step width (w_H: $-213\% \leq \%\text{Errors} \leq$

+223%). Conversely, our convention (Fig. 3B) yielded *no* errors at any step for any turn angle (l_P & w_P: all %Error = 0%).

[Insert Figure 3 About Here]

For *Lateral Lane Change* maneuvers (Fig. 4), Huxham's convention (Fig. 4A) yielded correct values ($l_H = L$; $w_H = W$) for only the first and last steps, but incorrectly distributes the maneuver (executed at a single step, by construction) across two consecutive steps (Fig. 4A), yielding counter-intuitive errors in both step lengths and widths at each step. Conversely, for our convention (Fig. 4B), because local path coordinates remain rightly aligned to lab coordinates (i.e., $[x',z'] = [x,z]$) across all steps, correct step lengths and widths are obtained at every step (Fig. 4B).

[Insert Figure 4 About Here]

For walking around *Circular Paths* (Figs. 5-6), both conventions yielded errors, as each approximated distances along a curve as straight lines. However, across all cases, Huxham's convention produced far larger errors (Fig. 5A) than ours (Fig. 5B). These increased rapidly with decreasing R_{Path} (Fig. 6). Huxham's convention yielded %Errors ~20 *times* (range ~2-40 times) larger for step lengths and ~140 *times* (range ~10-260 times) larger for step widths (Fig. 6A). These errors artificially introduced *large* stepping asymmetries (Fig. 6B) for steps purposefully constructed to be perfectly symmetrical. Conversely, our convention yielded exactly symmetrical ($USI = 0$) values (Fig. 6B), consistent with how stepping sequences were constructed.

[Insert Figure 5 About Here]

[Insert Figure 6 About Here]

Shifting $[x',z']$ away from the mid-point between the feet (0.5; Fig. 1B), towards either the trailing foot ($0.5 \rightarrow 0$; Fig. 2A) or leading foot ($0.5 \rightarrow 1$; Fig. 2B), increased error magnitudes, with %Errors for outside-to-inside steps exhibiting trends opposite to those of inside-to-outside steps (Fig. 7A). This artificially introduced substantial asymmetries in both step lengths and widths (Fig. 7B) for steps purposefully constructed to be perfectly symmetrical (Fig. 5). As expected however, setting $[x',z']$ at exactly 0.5 correctly yielded perfect symmetry ($USI = 0$; Fig. 7B), for any path curvature (Fig. 6B).

[Insert Figure 7 About Here]

For walking along the *Arbitrary Curvilinear Path* (Fig. 8), both conventions yielded errors that generally scaled with the sharpness of local path curvature: errors were largest at/near the two sharpest turns towards the beginning and end of the path. However, across the entire path, our convention yielded errors (Fig. 8D) that were approximately order-of-magnitude smaller than Huxham's (Fig. 8C).

[Insert Figure 8 About Here]

4. Discussion

Humans rarely walk in straight lines in the real world (Glaister et al., 2007). Older adults who are less able to adapt to such ever-changing task circumstances may be more likely to fall (Robinovitch et al., 2013) and incur serious injury (Burns and Kakara, 2018). Because spatiotemporal gait parameters are relatively easy to obtain and can help predict fall risk (Taylor et al., 2013), it is important to develop conceptually coherent ways to conceive these parameters for wide-ranging non-straight walking tasks. This work does just that.

We show that anatomically-based coordinates cannot work because they intrinsically conflate body segment motions with the walking task being performed (Supplement). The alternative convention proposed by (Huxham et al., 2006) (Fig. 1A) produces large artificial errors for single-step turns (Fig. 3A), introduces artificial changes in movement direction for lateral maneuvers (Fig. 4A), generates both substantial errors (Fig. 5A & 6A) and artificial asymmetries (Fig. 6B) for walking around circles, and excessively large errors for walking on general curvilinear paths (Figs. 8A & 8C). Conversely, our convention (Fig. 1B) returns exactly correct stepping values for both single-step turns (Fig. 3B) and lateral maneuvers (Fig. 4B), vastly smaller errors (Figs. 5B & 6A) and *no* artificial asymmetries (Figs. 6B & 7) for walking around circles, and vastly smaller errors for curvilinear walking (Figs. 8B & 8D). Most importantly, our convention directly generalizes original concepts and definitions from straight walking (Whittle, 2007), where steps

are defined relative to the task of walking on a (straight) *path*.

One might consider a limitation to this study to be that we present no examples applied to experimental data. However, like prior efforts (Ho et al., 2023; Huxham et al., 2006; Kainz et al., 2016) that did so, we would be able to demonstrate only that different conventions yield different values, as the "true" values can never be known for experimental data. Thus, the strength of this work is precisely that we *did* use idealized simulated data to represent perfect performance for each walking task. Only by doing so could we quantify actual accuracy of each compared result relative to known *true* values. The fundamentally conceptual questions our work answers could not have been addressed otherwise.

One might also reason that a potential limitation to our convention (Fig. 1B) is needing to know the (pre-defined) path the person is walking on. In experimental (lab) settings, walking tasks (and thus, paths) can readily be defined (explicitly or implicitly) by the experimenter (Acasio et al., 2017; Bland et al., 2019; Desmet et al., 2022; Ho et al., 2023). When studying real-world walking though (Bergsma et al., 2021; Glaister et al., 2007), this is less practical. Nevertheless, numerous studies confirm that people walk intentionally (Gordon et al., 2021) to achieve specific task objectives. To do so, they choose consistent (Moussaïd et al., 2011) and stereotypical (Hicheur et al., 2007) paths capturable by common optimization criteria (Arechavaleta et al., 2008; Brown et al., 2021; Pham et al., 2007). Thus, even when walking tasks have no specific defined path (Bergsma et al., 2021; Dixon et al., 2013), numerous approaches exist to identify one (Rudenko et al., 2020).

Our results strongly confirmed our hypothesis. Defining stepping parameters relative to the walking path (Fig. 1B) yielded *correct* results across more tasks, and more *accurate* results for each. Real world walking involves continuously making "embodied decisions" – we "decide as we act" while also "acting as we decide" (Gordon et al., 2021). To navigate complex spaces, people follow systematic, calculable trajectories (Arechavaleta et al., 2008; Moussaïd et al., 2011). They choose foot placements several steps in advance (Matthis and Fajen, 2014) and regulate their steps from step to step to achieve specific task goals (Dingwell et al., 2010). One explicit goal is to *stay on their path* (Dingwell and Cusumano, 2019), which people readily modulate when their path changes (Desmet et al., 2022). Present findings are fully consistent with these principles and extend the argument for treating walking as a *goal-directed* process, where tasks are theoretically defined prior to, and independent of how people perform those tasks (Cusumano and Dingwell, 2013).

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Figures & Figure Captions:

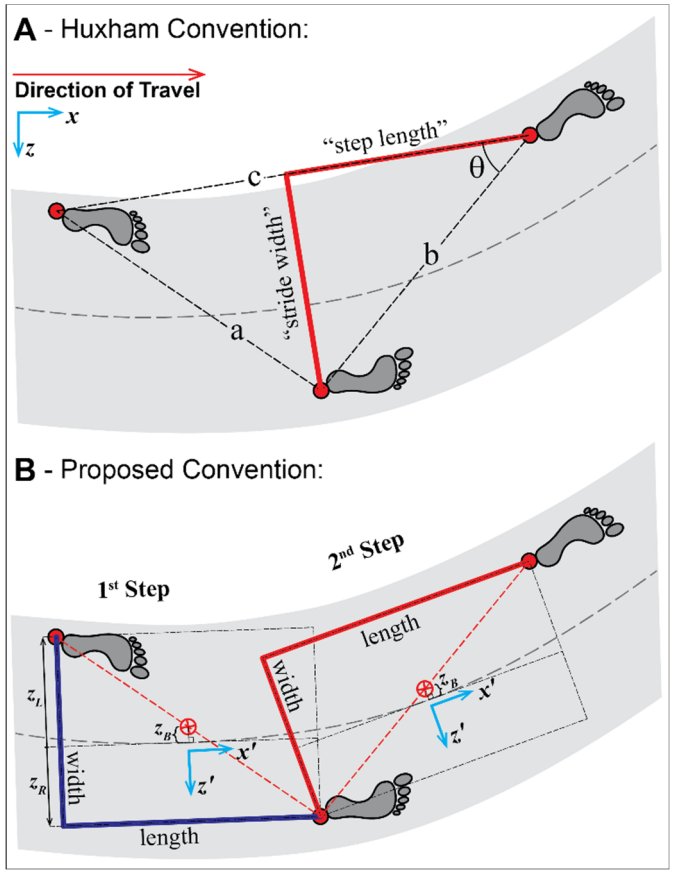

Figure 1 – Defining Stepping Parameters: A) The convention for defining step length and "stride width" proposed by Huxham et al., 2006. Given only the locations of three consecutive foot placements, the direction of forward progression (DoP) for the middle foot placement is taken as line "*c*", which connects the prior and subsequent contralateral foot placements. Huxham's step lengths (l_H) and "stride widths" (w_H) are then computed from basic trigonometric relationships: i.e., $l_H = b\cos(\theta) = (b^2+c^2-a^2)/2c$ and $w_H = \text{sqrt}(b^2-l_H^2)$ (Huxham et al, 2006). Of note, these relationships do not in any way account for where the feet are placed with respect to the walking path. **B)** The proposed convention presenting a path-based approach for the exact same three foot placements. Each step is considered its own true step, consisting of two foot placements only. The person's body position is taken as the midpoint between the two foot placements that make up that step (Orendurff et al., 2004; Dingwell & Cusumano, 2019). A local [x',z'] coordinate system is then aligned tangent to the path at the point on the path closest to the body position. Step lengths (l_P) and step widths (w_P) are then calculated in this path-defined local coordinate system just as they would be in fixed lab-based coordinates for typical straight walking.

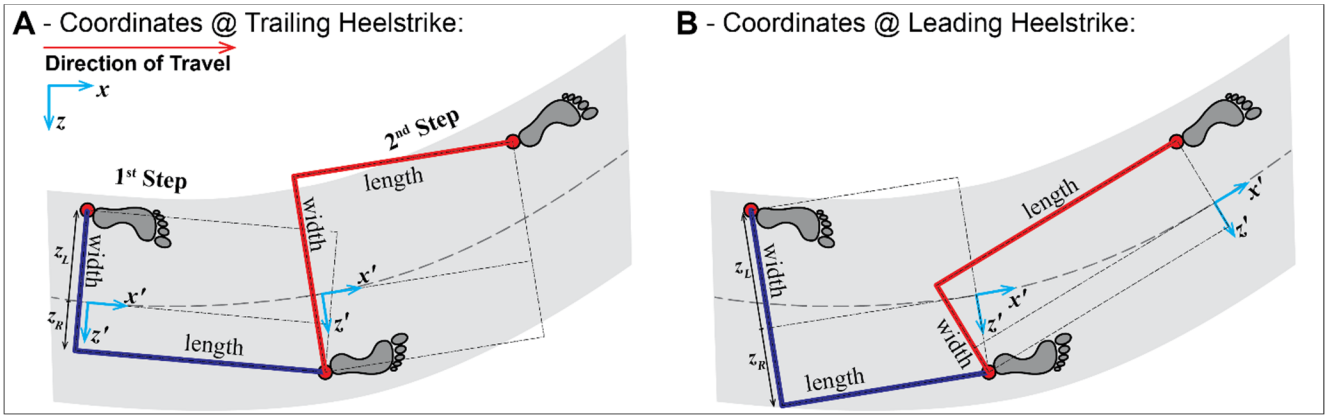

Figure 2 – Different Local Path Coordinate Choices. When [x',y'] are aligned with the midpoint between the two feet (Fig. 1B), step lengths and step widths are each similar for both steps. However, **A)** If [x',y'] were instead aligned with the trailing (rear) foot placement of each step, the 1st ("inside-to-outside") step becomes longer and narrower, while the 2nd ("outside-to-inside") step becomes wider and shorter. **B)** Conversely, if [x',y'] were aligned with the leading (front) foot placement of each step, the 1st step now becomes wider and shorter, while the 2nd step becomes longer and narrower.

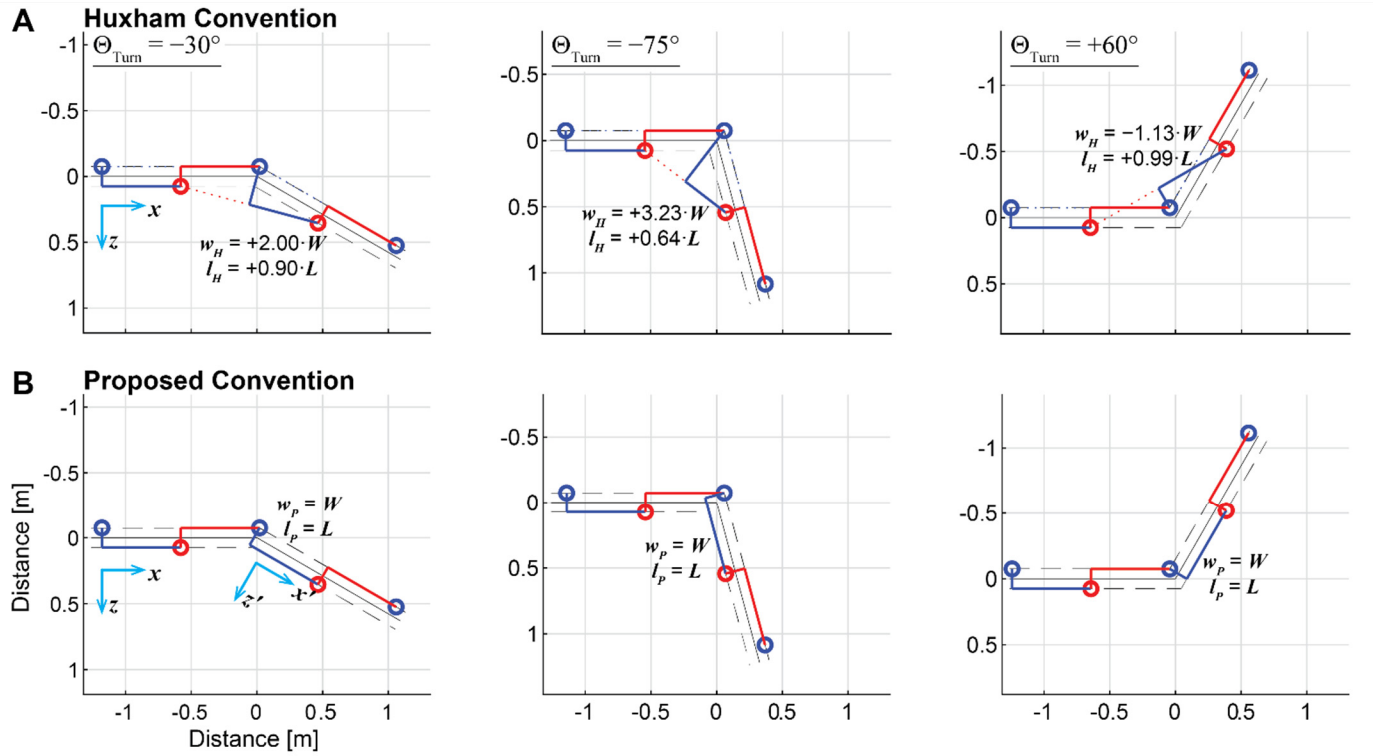

Figure 3 – Single Discrete Turns: All example sequences shown were constructed to walk from left-to-right, executing a single discrete turn at the 3rd step shown. Top and bottom panels show the exact same sequences of *steps*. **A)** The Huxham defined "stride widths" (w_H) and step lengths (l_H) for stepping sequences involving turns executed at a single step. Huxham's convention returns correct values ($w_H = W$; $l_H = L$) for all steps before and after the turn (not labeled). However, on the turn step itself, Huxham's calculations return values that markedly deviate from these. Step width %Errors are +100%, +223%, and −213%, while step length %Errors are −10%, −36%, and −1%, for the 3 turns shown above. These errors scale with the amplitude of turn, despite the fact that the steps themselves (by construction) do not. **B)** The proposed step lengths (l_P) and widths (w_P) for the same stepping sequences. Here, because the local [x',z'] coordinate system rotates with the turning movement on the step where the turn is executed, *all* steps in all sequences stepping return the correct values: i.e., $w_P = W$ and $l_P = L$ for all steps involved in all turns. The proposed methods thus yields 0 %Error for all measures for all steps, regardless of the magnitude of the turn executed.

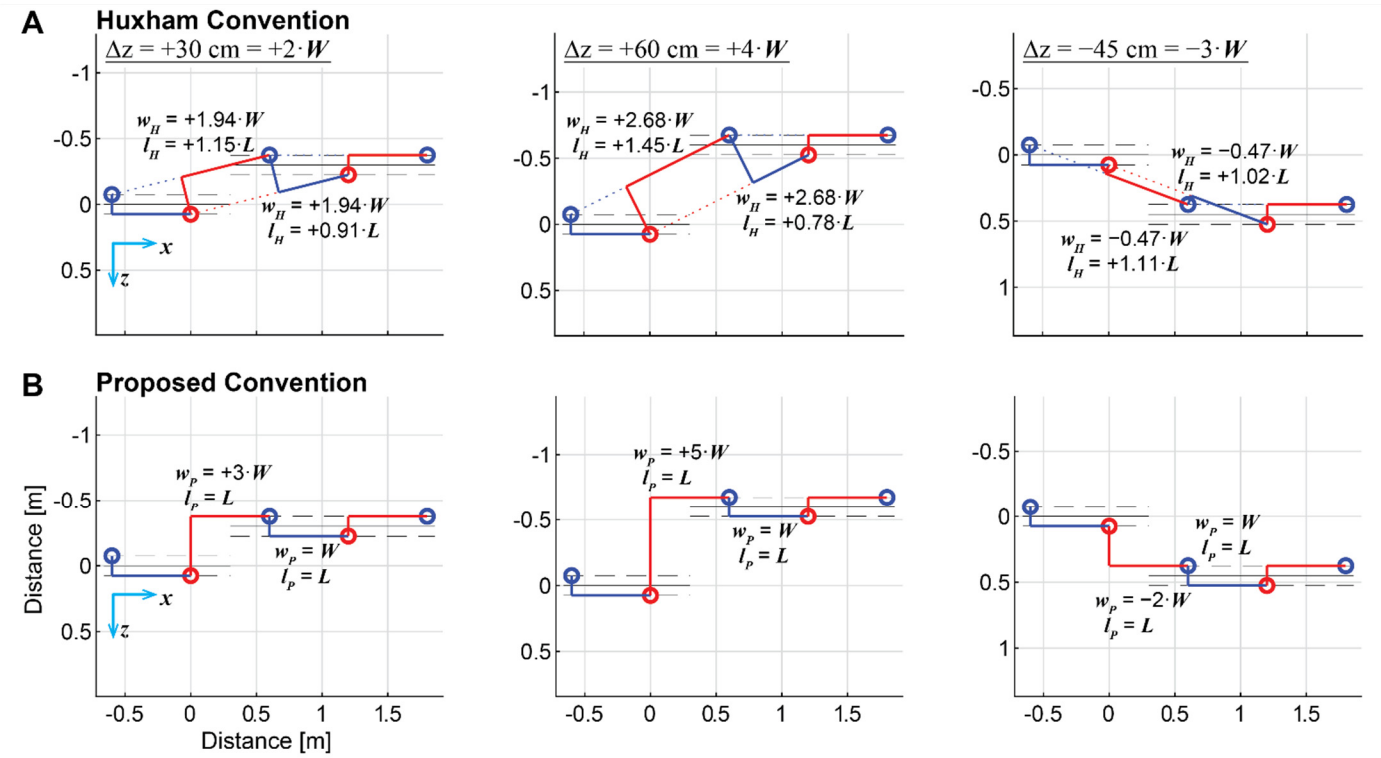

Figure 4 – Lateral Lane-Change Maneuvers: All example sequences shown were constructed to walk from left-to-right, executing a single lateral lane change after the 2nd step shown. Top and bottom panels show the exact same sequences of *steps*. **A)** The Huxham defined "stride widths" (w_H) and step lengths (l_H) for stepping sequences involving lateral lane-change maneuvers executed at a single step. Huxham's convention returns correct values ($w_H = W$; $l_H = L$) for the first and last steps shown. However, despite that these stepping sequences were explicitly constructed to enact each lane change at a single step, Huxham's convention necessitates distributing these maneuvers across two consecutive steps. In doing so, Huxham's calculations return values that markedly deviate from defined movements that generated these lane changes. **B)** Conversely, the proposed convention keeps the local coordinate system ($[x',z']$) at each step aligned to the paths, which in turn change only location and not direction. Thus, all steps in all sequences yield exact step lengths of $l_P = L$. The proposed method likewise yields exact step widths of $w_P = W+\Delta z$ for the step that executes each lane change and $w_P = W$ for all other steps in every sequence. The proposed methods thus yields 0 %Error for all measures for all steps, regardless of the magnitude of the lateral lane change executed.

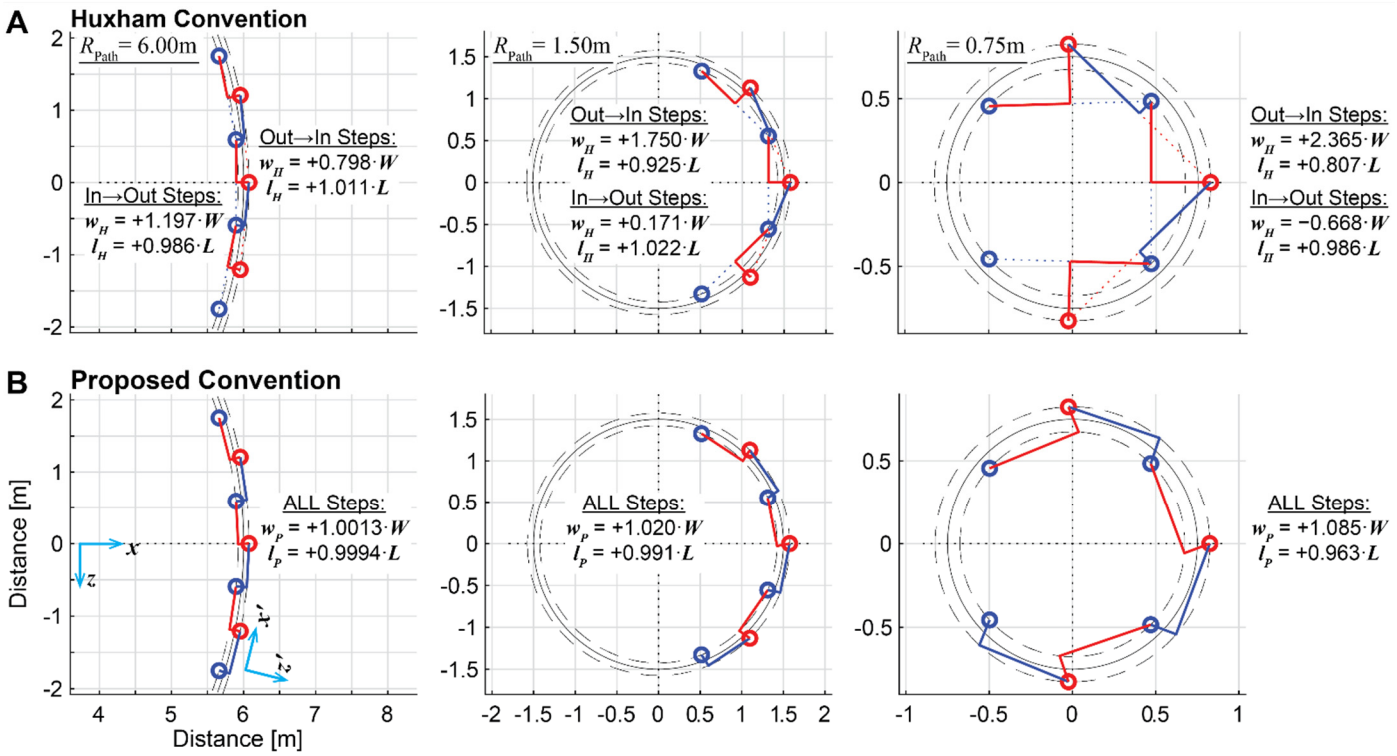

Figure 5 – Continuous Walking Around a Circle: All example sequences shown were constructed to walk in a counter-clockwise direction around each circular path. Top and bottom panels show the exact same sequences of *steps*. **A)** The Huxham defined "stride widths" (w_H) and step lengths (l_H) for each stepping sequence. Because of how w_H and l_H are constructed (Fig. 1A), Huxham's convention yields markedly different values for outside-to-inside ("out→in"; here, right-to-left) vs. inside-to-outside ("in→out"; here, left-to-right) steps. As shown, the deviations from the correct values ($w_H = W$; $l_H = L$) increase dramatically as the radius of the circular path (R_{Path}) gets smaller. **B)** The corresponding proposed step widths (w_P) and lengths (l_P) for the same stepping sequences. Because the proposed convention keeps the local coordinate system ([x',z']) at each step aligned tangent to the path at that step, and all steps were defined (by construction) equivalently, the proposed method yields the *same* w_P and l_P values for *all* steps, both outside-to-inside and inside-to-outside. While these values are not *exact* (due to approximating curvilinear motion as a straight line within each step), the deviations from the correct (defined) values (i.e., $w_P = W$ and $l_P = L$) are clearly far smaller than for the Huxham convention.

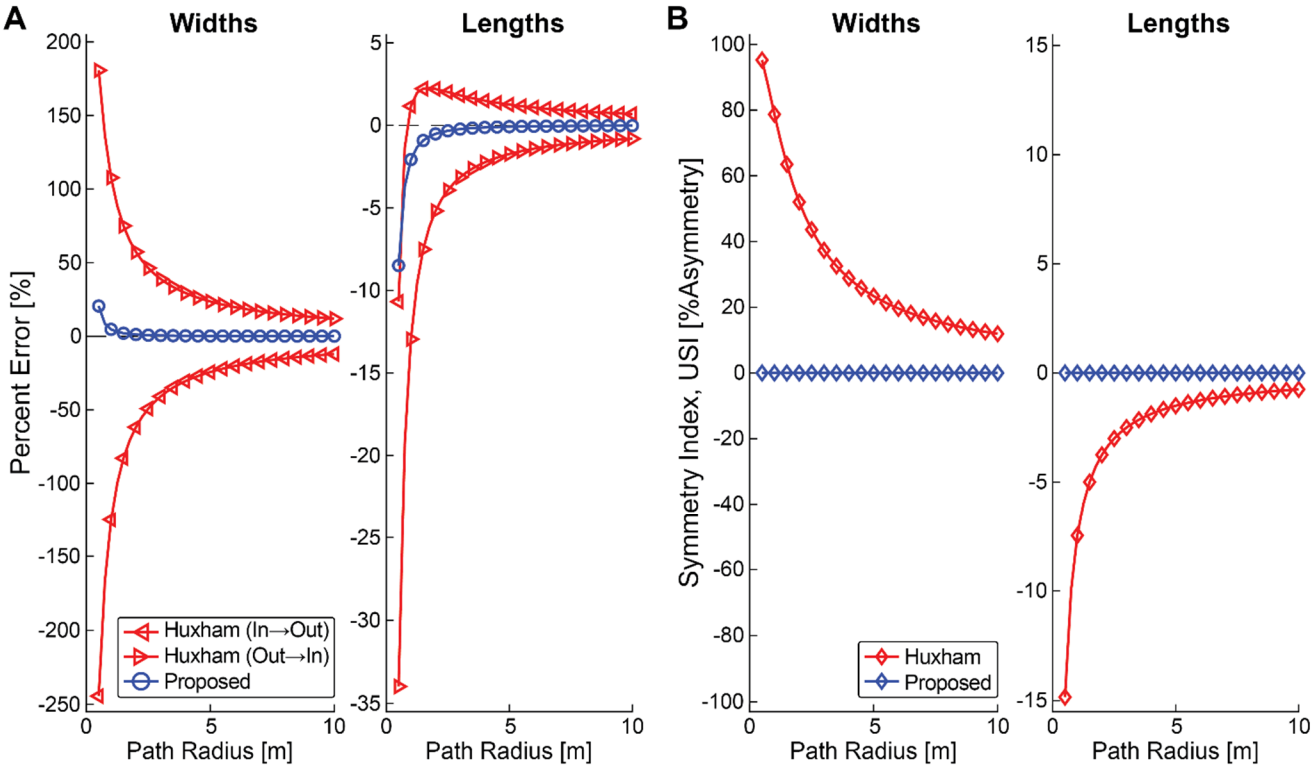

Figure 6 – Stepping Percent Errors for Walking Around Circles: A) Percent stepping errors (%Error; Eq. (2), Methods) relative to their prescribed values, plotted versus circular path radius (R_{Path}) for both step widths (left) and step lengths (right) for both the Huxham and proposed conventions. Note positive %Errors reflect larger-than-prescribed stepping parameter values, while negative %Errors reflect smaller-than-prescribed stepping parameter values. For very large path radii (i.e., as $R_{Path} \rightarrow \infty$), both methods eventually converge to zero (0) %Error for straight walking. However, although %Errors for both methods tend to increase approximately exponentially as R_{Path} gets smaller, these errors are consistently at least ~1-2 orders of magnitude smaller for our proposed convention (Fig. 1B) than for Huxham's (Fig. 1A). **B)** Universal Symmetry Index (*USI*; Eq. (3), Methods) values reflecting relative asymmetries between inside-to-outside and outside-to-inside steps for the data shown in (A). Step widths and step lengths were both highly asymmetrical for the Huxham convention. Conversely, our proposed convention yielded perfectly symmetrical steps (consistent with how the steps were constructed), for all path radii.

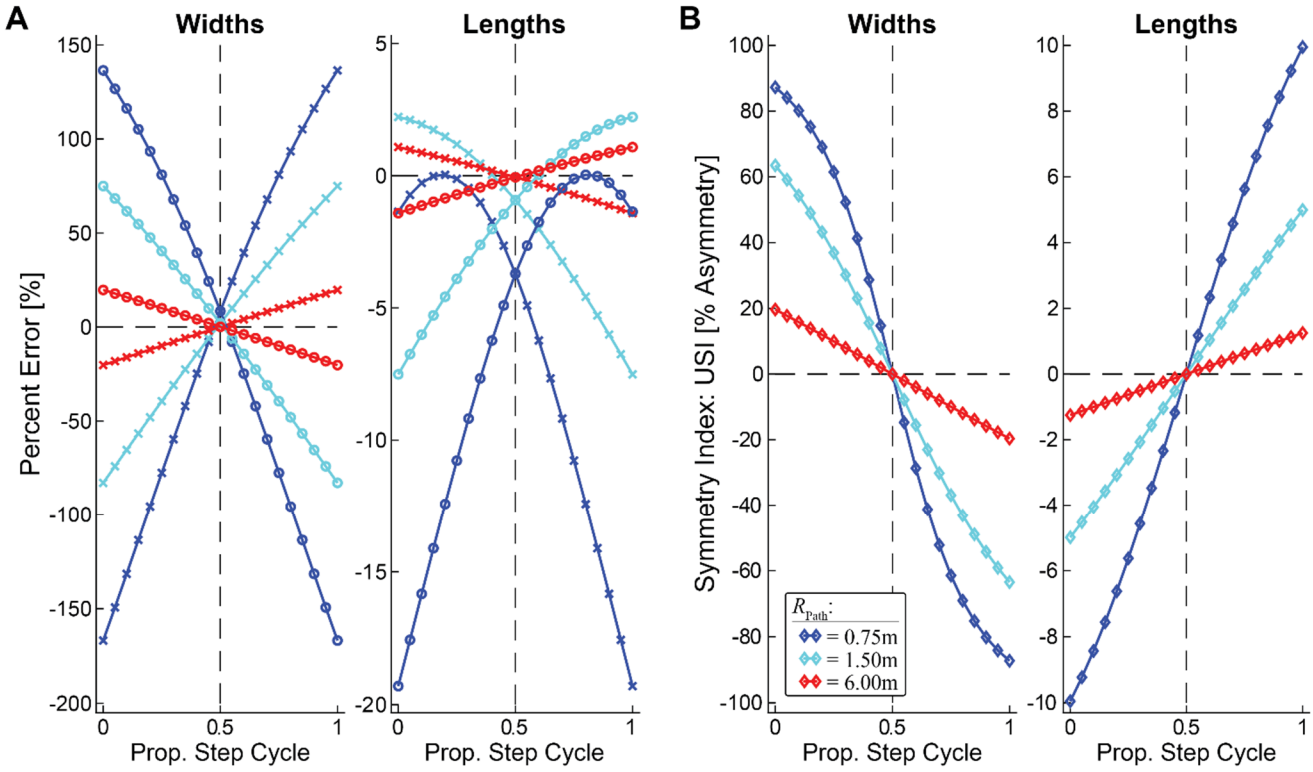

Figure 7 – Stepping Percent Errors vs. [*x′,y′*] Location For Our Proposed Method: A) Percent stepping errors (%Error; Eq. (2), Methods) as computed with [*x′,y′*] set at different proportions of the gait cycle, starting from the location of the trailing foot (0; Fig. 2A) to the location of the leading foot (1; Fig. 2B). %Error data are for inside-to-outside (×) and outside-to-inside (○) steps for circular paths of the same path radii as in Fig. 4 (i.e. R_{Path} = {6.00, 1.50, 0.75} m). %Error magnitudes generally increased as [*x′,y′*] was shifted away from the mid-point between the feet (0.5) towards either the trailing foot (0.5 → 0) or leading foot (0.5 → 1). Trends for inside-to-outside steps were opposite to those of outside-to-inside steps. **B)** Universal Symmetry Index (*USI*; Eq. (3), Methods) values reflecting relative asymmetries between inside-to-outside and outside-to-inside steps for the data shown in **(A)**. Step widths and step lengths were symmetrical *only* when [*x′,y′*] was taken at the midpoint between the feet (0.5), and strongly *a*symmetrical otherwise, especially for step widths.

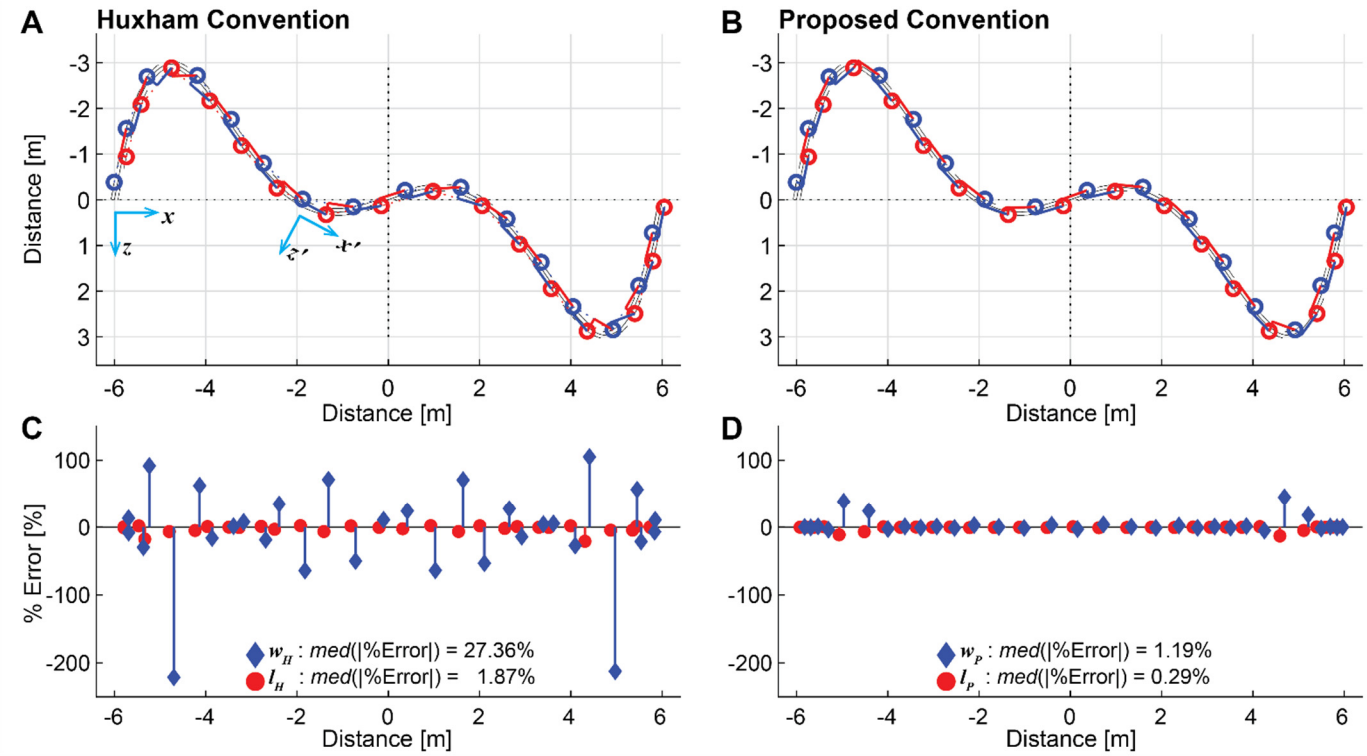

Figure 8 – Continuous Walking Along an Arbitrary Path: A single sequence of 32 consecutive steps was constructed to walk along a curvilinear path defined as a 5th order polynomial (see Methods). General direction of progression is from left to right. Panels (**A**) and (**B**) show the exact same sequences of *steps*. **A)** Huxham defined "stride widths" (w_H) and step lengths (l_H) for this stepping sequence. **B)** The corresponding proposed step widths (w_P) and lengths (l_P) for the same stepping sequence. **C)** %Errors at each step for both step widths (◊) and lengths (○), as computed following the Huxham convention. **D)** Corresponding %Errors at each step, as computed following the proposed convention. For both methods, the largest errors occurred at points of sharpest curvature, consistent with Figs. 4-5. Across all steps in this sequence, %Errors were consistently ~order-of-magnitude smaller for the proposed convention than for the Huxham convention, also consistent with Figs. 4-5. This was confirmed by computing the median (*med*) absolute %Error (i.e., |%Error|) across all steps in the sequence, as indicated on each plot.