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Aperture passability judgments in novice walker users: The impact of action scaling above and beyond body scaling

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APERTURE PASSABILITY JUDGMENTS OF NOVICE WALKER USERS: THE IMPACT OF ACTION SCALING ABOVE AND BEYOND BODY SCALING

A Thesis
Presented to
the Graduate School of
Clemson University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science
Applied Psychology

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by
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ABSTRACT

Many older adults who use assistive walking devices to improve stability and locomotion also report falls while using their device. The present study investigated how walking devices alter the perception-action system of the user. Specifically, the study assessed how walker users perceive their ability to pass through a doorway. One's ability to pass through an aperture is constrained by their widest frontal dimension (body-scaling) and the dynamic properties of the individual in motion (action-scaling). In order to compare the unique impacts of body-scaling and action-scaling, novice users of a standard walker, wheeled walker, cane, or no device (control) made static and dynamic judgments of aperture passability while their lateral motion variability was recorded. Hierarchical Linear Modeling revealed that novice users successfully scaled their passability judgments to the width of the walker, and that the introduction of movement for the dynamic judgments resulted in more conservative perceptions of passability. Unexpectedly, motion variability was not a significant predictor of passability judgments, which suggests that the self-motion produced during dynamic judgments revealed additional environmental information (rather than intrinsic dynamic information) and allowed for the application of a margin of safety. Results of this study suggest that experience using the walking device is an important factor in ensuring new users understand their action capabilities and avoid injurious collisions and falls.

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CHAPTER ONE

INTRODUCTION

Assistive walking devices are used by older adults to improve stability and allow independent locomotion (Bateni & Maki, 2005). Despite their benefits, falls still occur in older adults who use walkers (Gell, Wallace, LaCroix, Mroz, & Patel, 2015; Charron, Kirby, & MacLeod, 1995). Past research has sought to determine whether the walker itself is causing the fall, but most of this research uses a biomechanical or cognitive approach. For instance, walkers have been shown to produce destabilizing effects (Bateni & Maki, 2005) and interfere with lateral compensatory stepping movements (Bateni, Heung, Zettel, Mcllroy, & Maki, 2004; Maki et al., 2006), as well as demand high levels of attention (Wright & Kemp, 1992). Despite this research, the device's effects on the human perceptual system have yet to be studied.

Research suggests that variability within the older adult population is greater than variability between older adults and other age groups (Hultsch, MacDonald, & Dixon, 2002). Additionally, older adults tend to have more intra-individual variability in their performance on cognitive (Hultsch, MacDonald, Hunter, Levy-Bencheton, & Strauss, 2000) and sensorimotor tasks (Callisaya, Blizzard, McGinley, Schmidt, & Srikanth, 2016), as well as increased within-person variability for gait (Callisaya, Blizzard, Schmidt, McGinley, & Srikanth, 2010), stability (Singer, Prentice, & McIlroy, 2013), and postural control (Huxhold, Li, Schmiedek, Smith, & Lindenberger, 2011). This intra-individual variability predicts cognitive and motor decline, and increases the likelihood of falls in older adults (Bauermeister et al., 2016). Due to this propensity for within-person changes, a framework that recognizes these intra-individual differences would be best suited to understand the perceptual-motor effects of walking devices on older adults.

With its emphasis on the coupling of perception and action, as well as its use of the actor-environment relationship as the unit of analysis, ecological psychology provides an appropriate framework. Affordances - a term coined by James Gibson (1979) - represent possibilities for action (e.g., walk-ability, climb-ability, reach-ability, etc.) that are directly perceived by an organism. Affordances are what can be done in one's environment. They are determined by the relationship between characteristics of the environment and properties of the organism's action system. Importantly, affordances are scaled to the individual organism, determined by each individual's morphology and physical capabilities. Additionally, affordance perception is sensitive to both gradual (Franchak & Adolph, 2014) and abrupt (Wagman & Taylor, 2005) changes in an individual's action capabilities, which could provide appropriate theory that accommodates intra-individual differences in older adults.

Individuals utilize two sources of intrinsic information in order to determine their affordances. First, individuals will use their intrinsic body scaling – their geometric properties and physical morphology – to determine their action capabilities (Ishak, Adolph & Lin, 2008). For example, a chair is sit-on-able if the height of the seat is lower than the height of the individual's knee. Because of this, a chair may afford sitting to an adult, but not to a small child. The physical dimensions (e.g., height, leg length) of the child restrict their ability to sit in the chair.

Second, in a process called action-scaling, individuals consider their dynamic properties (e.g., flexibility, strength, dexterity, etc.) when determining if an action is possible (Konczak, Meeuwsen, & Cress, 1992; Cesari, Formenti, & Olivato, 2003; Cesari, 2005). Dynamics represent those properties that are causally involved in determining a course of movements, which is particularly useful because it informs one's affordances (Runeson & Frykholm, 1983). Consider a chair whose seat is placed very low to the ground. The chair may be sit-on-able according to body-scaled requirements (since the height of the seat is lower than the height of the knee), but the individual may not be capable of sitting depending on their hip flexibility, leg strength, and balance. Thus, two individuals with similar physical dimensions may have differences in affordances based on different dynamic capabilities. Overall, both body-scaling and action-scaling determine what an individual can and cannot do in their environment.

Since avoiding collisions with objects in the environment is a crucial task during all ambulatory movement, the present experiment will study the perceptions of aperture passability in novice walker users before, during, and after using the walkers. By studying perceptual judgments of novice users before and after they have used the walker, insights can be gained into the impact of action-scaling on perceptions of passability above and beyond the information provided by body-scaling. Of course, there are many different types of assistive walking devices, and each may affect affordance perception differently. Therefore, the purpose of this study is to examine differences in static and dynamic aperture passability perception between multiple types of assistive walking devices.

Use of body-scaling for determining aperture passability

Individuals determine their ability to pass through an aperture by comparing the width of the opening with their widest frontal dimension - their shoulder width. Warren and Whang (1987) found that regardless of body size, humans use intrinsic scaling of their own geometric dimensions to determine if an aperture affords passing. Tall and short participants walked at a normal speed through doorways of various widths. Results showed that participants altered their gait by rotating their body while passing through the door (a strategy used to avoid collision with the door frame) when its width was 1.3 times their shoulder width. Later, participants were asked to make standing yes or no judgments as to whether they could pass through doorways of various widths without turning their shoulders. Again, participants judged the boundary between passable and impassable door widths to be a ratio of 1.16 times their shoulder width. Thus, regardless of their body size, each participant scaled their aperture passability to their own individual shoulder width.

Since the body naturally changes in shape and size throughout the lifespan (e.g., through developmental growth, weight gain/loss, or pregnancy), our affordances also change (Adolf, 2008; Adolph & Avolio, 2000; Franchak & Adolph, 2014). Importantly, individuals successfully scale their affordances to their changing body-dimensions. For example, as women progress through their pregnancy, they undergo gradual increases in body weight and stomach circumference. As expected, pregnant women will judge their aperture passability in relation to their gradually changing body (Franchak & Adolf, 2014).

In addition to scaling affordances to our naturally changing body dimensions, altered body states brought upon by external tool use will also affect action capabilities (Shaw, Flascher, & Kadar, 1995). When a tool is attached to the body of its user, it becomes functionally incorporated into the body, which changes the body's geometric properties. Thus, the width of the resulting person-plus-object system must be taken into account when determining aperture passability. Wagman and Taylor (2005) presented varying door widths to participants who were holding a T-shaped object, and asked them to give a yes or no judgment as to whether they could walk through the aperture while keeping the object horizontal and their shoulders facing forward. Judgments of aperture passability were scaled to the person-plus-object's widest frontal dimension. When the objects were wider than the participant's shoulder width, judgments were scaled to the width of the object; When objects were smaller than the participant's shoulder width, judgments were scaled to the participant's shoulders.

Furthermore, in novice wheelchair users, both static judgments and dynamic actions of aperture passability were scaled to the width of the wheelchair (Higuchi, Takada & Imanaka, 2004; Higuchi, Cinelli, Greig & Patla, 2006). Additionally, teleoperators of remote robots scale their judgments of the robot's aperture passability to the widest dimension of the robot (Moore, Gomer, Pagano & Moore, 2009; Mantel, Hoppenot, & Colle, 2012; Jones, Johnson, & Schmidlin, 2011). Unlike changes in body dimensions brought upon by natural growth, the introduction of an external tool may cause instantaneous and drastic changes that must be considered when determining action capabilities. This suggests that both gradual and abrupt changes in the user's body dimensions are immediately perceived during the body-scaling of affordances (see also Day, Ebrahimi, Hartman, Pagano, Babu, 2017).

Use of action-scaling for determining aperture passability

In addition to being body-scaled, aperture passability is also action-scaled; one must take into consideration not only the geometrical width of their body, but also the width of their body while it is in motion (Franchak, Celano & Adolph, 2012). Action-scaling necessarily uses geometric information, but enhances that information by calibrating the body-scaling to consider one's dynamic capabilities. For example, when older adults walk, they produce more lateral shoulder sway than younger adults. In other words, the spatial requirements for walking exceed the geometric dimensions of the individual. Because of this increase in their dynamic lateral dimension, older adults tend to require larger apertures before judging them to be passable compared to younger adults with the same shoulder width (Hackney & Cinelli, 2013).

There is ample evidence to support the theory that higher motion variability from old age (Hackney & Cinelli, 2013), developmental coordination disorder (Wilmut, Du & Barnett, 2015), and high speed movement (Higuchi, et al., 2011; Wagman & Malek, 2007) results in an increase in the judged passability boundary widths and the use of a larger margin of safety when passing through apertures. Thus, overall judgments of aperture passability are both body-scaled to one's physical dimensions and action scaled to the spatial requirements of one's movements.

Static and dynamic affordance perception

Since novice walker users are unfamiliar with the dynamic properties associated with moving the walking device, it may be difficult for them to initially utilize action scaling information. Muroi and Higuchi (2016) suggested that static vision from a distance provided adequate information to guide future actions of walking through an aperture with an altered body state. However, the altered body state was achieved by having participants hold a long rod. This manipulation likely had a minimal effect on the participant's dynamic properties, which allowed them to rely on their past walking experience to successfully engage in action-scaling. Nonetheless, this implies that performing the relevant movement is not necessary in order to accurately perceive affordances.

A competing argument suggests the opposite – that action *is* required in order to perceive one's affordances, especially when the affordance depends on dynamic characteristics. Indeed, baseball players are more accurate at determining if a fly ball is catchable if they initiate their movement towards the ball (Oudejans, Michaels, van Dort, & Frissen, 1996). Similarly, pedestrians are more accurate at determining if they can safely cross a street with oncoming traffic when they take one step towards the road (Oudejans, Michaels, Bakker, & Dolne, 1996). In these cases, even just the initiation of task relevant movement allows individuals to determine their ability to complete an action because it provides the dynamic information necessary to engage in action-scaling. Exploratory movements (that are not task-specific) can also be utilized to inform affordance perception so long as the optic flow is coupled to the self-produced motion

(Bingham & Pagano, 1998; Gomer, Dash, Moore, & Pagano, 2009; Mantel, Stoffregen, Campbell, & Bardy, 2015; Srinivasan, 1992).

A third argument states that individuals can successfully perceive affordances during a static judgment only after they know their locomotor capabilities (Fajen, Diaz, & Cramer, 2011). For novel forms of locomotion, this would require calibration to the new dynamic characteristics. As individuals move through their world, they learn about the changes in optic flow that are associated with given biomechanical patterns (Gibson, 1979). Thus, it is through experience with a given locomotion form that individuals can calibrate and learn how their movements influence optic flow (Rieser, Pick, Ashmead, & Garing, 1995). For example, novice wheelchair users who engaged in non-specific practice had higher accuracy on a passability judgment task than novice users who did not receive practice time (Stoffregen, Yang, Giveans, Flanagan & Bardy, 2009). The practice session allowed novices to learn about the kinematic patterns from the dynamic properties of the wheelchair, which provided sufficient information about the person-plus-object system's dynamic capabilities to later produce accurate static judgments of passability.

Perhaps the use of action scaling underlies each of these arguments, such that static viewing only allows for geometric body scaling while action (either current or past active experience) is required to pick up on the additional dynamic action-scaling component. The following study seeks to further explore the role of action-scaling on aperture passability judgments and assess its effects on affordance perception above and beyond that information provided by body-scaling.

Present study

In the present experiment, novice users of either a standard four footed walker, a front-wheeled walker, a cane, or no device (control) made both static and dynamic aperture passability judgments. Canes and walkers differentially affect the geometric dimensions of the person-plus-object system. Walkers consist of a 4 legged frame that surrounds the user and will increase their functional width. Canes, on the other hand, do not surround the user, and can be placed in front of the user such that there is no increase in body width. Therefore, based on body-scaling alone, cane users are likely to judge smaller door widths to be passable compared to users of the standard and wheeled walkers.

Additionally, each type of assistive walking device may differentially affect the lateral motion variability of the user, resulting in different spatial requirements for locomotion. Whereas the front-wheeled walker has fixed wheels that move directly forward when pushed, the standard 4-footed walker requires lifting the device with every step. By introducing the requirement to lift the device, the standard walker increases the number of degrees of freedom for movement, which should subsequently increase the amount of motion variability associated with its use. Thus, even though the physical width of the walker remains constant for both conditions, larger aperture passability judgment boundaries are expected for the standard walker compared to the wheeled walker due to action-scaling. Successful use of action scaling in this instance would require the user to consider the motion variability of the walker itself since the walker is the widest frontal dimension. However, using the device may also alter the participant's natural gait and shoulder sway. Although the shoulders are not the widest frontal dimension of the person-plus-object system, a change in their typical motion variability may also be considered when engaging in action scaling. Therefore, motion variability data was collected separately for both the walking device and the participant's shoulders and both were included in analyses.

Participants made their passability judgments in three distinct phases. In the first Static phase (Static 1), participants stood 2 m from the aperture and made passability judgments while holding the walking device. Since there was no opportunity to practice or use the device in order to learn about its dynamic properties, judgments from this phase were expected to utilize only body scaling information. Next, in the Dynamic phase, participants used their device to walk from the beginning of the path to the 2 m line and then make their judgment. In this phase, participants were exposed to the motion variability and spatial requirements of using the device, and were expected to engage in action-scaling when determining their passability. Lastly, in the second Static phase (Static 2), participants again stood 2 m from the aperture and made judgments while holding the device. Judgments from this phase served to test for a carryover effect. That is, since participants had already been exposed to the dynamic properties of the walking device during the previous phase, assessing their judgments in this phase tested to see if they had recalibrated the perceptions of their action capabilities to consider their dynamic capabilities.

The main hypotheses for this study are presented below.

H1) Users of the standard and wheeled walker will have larger critical passability widths than cane users and the control group for all phases.

H2) Critical passability widths for the first Static phase will be smaller than for the Dynamic phase and the second Static phase.

H3) The effect of phase (H2) will be moderated by walker type, such that the control condition will show no change in critical passability width across phases, the cane will show small changes across phases, and the standard and wheeled walkers will show the largest changes across phases.

H4) Trial by trial motion variability will predict Dynamic passability judgments, such that higher motion variability on a given trial will reduce the likelihood of an aperture being judged as passable.

H5) Motion variability aggregated to Level 2 (that is, the average of each trial's motion variability for each participant) will predict passability judgments for the Dynamic judgments and the second phase of Static judgments, but not the first phase of Static judgments.

CHAPTER TWO

METHOD

Participants

Forty Clemson University undergraduate students participated in the study for partial course credit (32 females, age *M* = 18.5, *SD* = 0.9). Prior to participation, all were screened to ensure that they had normal or corrected-to-normal vision, no motor impairments, and no prior experience using assistive walking devices.

Simulation studies investigating the power of Hierarchical Linear Models suggest that the number of participants and the number of trials are both important for establishing sufficient power (Hofmann, 1997). To determine the Level 2 sample size (number of participants), a power analysis using Cohen's large effect size of .4 (Cohen, Cohen, West, & Aiken, 2003) and an alpha of .05 revealed that a sample size of 40 participants will produce power above .85.

To determine the Level 1 sample size (number of trials), the nested-ness of the data must be taken into account. Data from each trial will be nested within participants, such that some of the within-participant variance will be accounted for by between-subject variables. In this case, the number of trials is not an accurate representation of the number of independent observations. The Intra-Class Correlation (ICC) is an index of nesting and can be used to adjust the number of trials so that it represents the effective sample size of independent observations (Bickel, 2007). Using this adjustment with an ICC ranging from .25 to .35, 126 trials per participant would produce an effective total sample size ranging from 113 to 156. Power analyses using Cohen's medium effect size of .3 and an alpha of .05 revealed that both effective sample sizes would produce power levels above .99. This is sufficient power to detect cross-level interactions (Van Der Leeden & Busing, 1994).

Materials and Apparatus

Assistive walking devices. A standard four-footed folding walker was used (model num. MDS86410KDBW, Medline Industries, IL). This model was chosen because the front legs could be easily interchanged with legs that have 5 inch wheels attached, which allowed the use of the same walker frame for both the standard walker and the wheeled walker conditions. The widest frontal dimension of the walker (measured as the distance between the front legs) was 58 cm. For the wheeled walker, the wheels were placed on the inside of the frame to ensure that the frontal width of the standard and wheeled walkers were equal. Wheels were fixed so to only move in the forward and backward directions.

For the cane condition, a standard offset handle cane was used (model num. MDS86420H, Medline Industries, IL). All assistive walking devices were equipped with push-button height adjustment capabilities. Participants were fitted to their device according to the device instructions, such that the height of the handgrips matches the height of the participant's wrist crease. Prior to the experiment, participants were given instructions on the proper use of their device.

Aperture. The experiment was run in a 7.5 X 4.5 m room, with a grey carpet path 1 m wide extending the length of the room. The path extended 5 m in front of the aperture, with a judgment line placed 2 m in front of the aperture. The aperture was created by a 7 ft wooden doorframe with a single sliding door that allows for the manual adjustment of the aperture width. On one side of the aperture is a 48 inch long wooden wall that hides the sliding door, and the other side consists of a 4 inch doorframe. A curtain was hung along the back wall to remove any background visual information that may help participants estimate the width of the aperture (See Figure 2.1).

Figure 2.1. Experiment room set-up: aperture and pathway.

Motion Tracking. The HTC Vive system (HTC, Taiwan) was used to collect motion variability data. Two Vive Base Stations were mounted onto standard tripods and positioned 7 feet above the ground at a 45-degree angle. The base stations were placed across from each other on both sides of the midpoint of the walking path. This configuration was chosen so that the data output would lie on the appropriate axis without requiring further rotation or transformation before analysis. The use of two base stations increased the precision of the data and prevented any lost data due to occlusion.

In order to acquire motion tracking data about both the participant's body and the walking device, multiple HTC Vive Trackers were used. Since the shoulders are the widest frontal dimension on the human body, trackers were placed above each shoulder by securing trackers to a backpack's shoulder straps using screws and a 3D printed plastic insert. A tracker was mounted to the walker at the center point of the top cross-bar. Lastly, a tracker was mounted to the cane just beyond the padded handle. For each participant, there were at most three active trackers: on the right shoulder, the left shoulder, and the assigned walking device (if applicable). For each tracker, positional data along the X, Y, and Z axes was collected at a sampling rate of 60 Hz. Data was sent to a Dell laptop computer through a SteamVR program.

Procedure

After giving consent, participants completed a short questionnaire that collected demographic information and asked participants if they had any prior experience using walking devices. After passing the initial screening criteria, participants were asked to put on the backpack that contained the motion trackers. The experimenter helped the participants to adjust the shoulder straps until the motion trackers were directly on top of the participant's shoulders.

Participants were randomly assigned to one of four walking device conditions: standard walker, wheeled walker, cane, or no device (see Figure 2.2). Participants were properly fitted to their device and given instructions for its use.

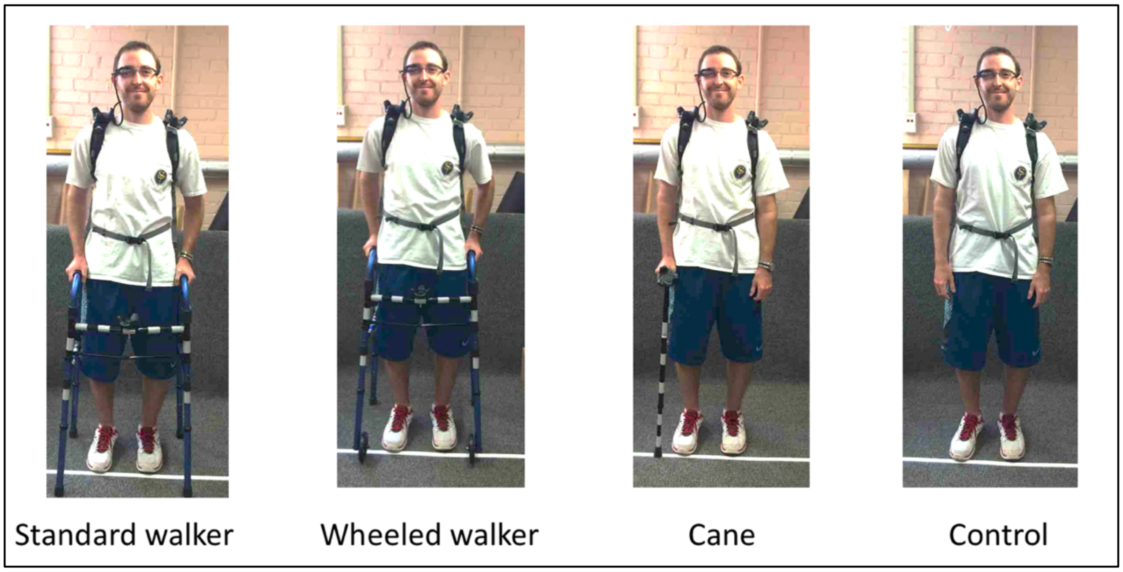
Standard walker
Wheeled walker
Cane
Control

Figure 2.2. Walker type by Condition.

For the experiment, participants performed an aperture passability judgment task. Participants stood in front of the aperture, were presented a specific door-width, and made a verbal judgment as to their perceived passability ("Yes" if the aperture is passable, "No" if the aperture is impassable). Participants never physically attempted to walk through the aperture, and thus they received no feedback about the accuracy of their judgments. In between trials, participants closed their eyes as the experimenter manually adjusted the width of the aperture.

Fourteen door widths were used as stimuli, ranging from 33 to 72 cm in 3 cm increments. Since the possible frontal widths of each participant could vary widely (from 39 cm in the control condition to 58 cm in the walker condition), these fourteen widths were chosen so that there would be at least 2 increments above and below each participant's widest dimension. Pilot testing revealed that perceived passability boundaries in the walker conditions exceeded two increments above the actual width, so additional door widths were included to ensure that passability boundaries could be obtained for each participant in each condition.

The experiment took place across three phases within a single experimental session. In each phase, participants were presented with 42 trials (14 door widths presented three times each) in a randomized order. The order of phases was presented as follows: 1) Static judgment task, 2) Dynamic judgment task, 3) Static judgment task.

In Phase 1 (static judgment task), the assigned walking device was placed at the judgment line (2 meters from the aperture) by the experimenter. The participant then stood behind the judgment line and held their device. Passability judgments were made for 42 trials as the participant stood at the judgment line holding their assigned device. It is important to note that prior to making their judgments in Phase 1, participants had no experience using their walking device; they simply stood in place and held the device for the duration of the phase.

In Phase 2 (dynamic judgment task) participants held their device at a starting line 5 m from the aperture. For each trial, participants used their walking device to walk forward and stop at the judgment line. Once stopped, they made their passability judgment. Participants then picked up their device and returned to the starting line for the next trial. By picking up the device when returning to the starting line, participants received no additional experience using the device in between trials. Thus, participants received information about the motion properties of the device only during the 42 dynamic judgment trials, and that information was restricted to the action of walking directly forward 3 meters at a time.

In Phase 3 (static judgment task), participants again stood behind the judgment line (2 m from the aperture) and held their device while making passability judgments for 42 trials. Since Phase 3 always occurred directly after the dynamic judgment task, participants now had some prior experience using their walking device (See Figure 2.3).

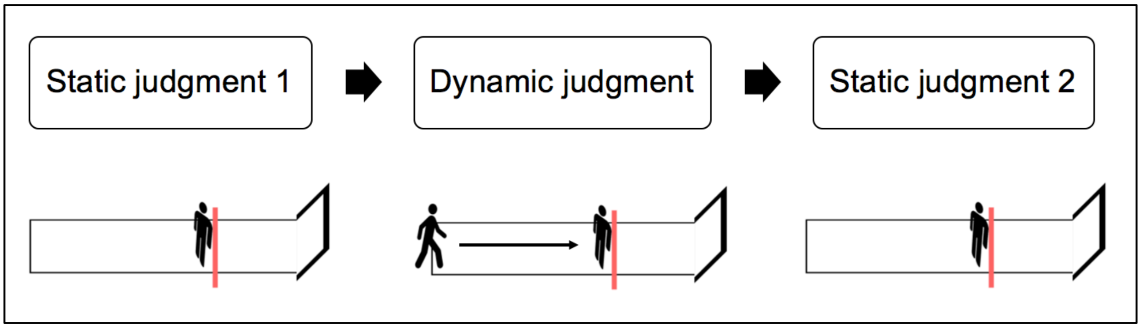

Figure 2.3. Judgment type by Phase.

At the conclusion of the three phases, the experimenters removed the equipment from the participant, recorded the participant's height and shoulder width, and provided debriefing. Each session lasted 45 minutes.

Motion Variability

Motion variability for each trial was operationalized in two ways: as the standard deviation of the lateral position (SDLP), and as the sample entropy (SampEn), calculated offline using the positional data along the lateral axis. The SDLP is used frequently in driving studies to quantify lane deviation (Verster & Roth, 2011; Marcotte, Scott, Lazzaretto, & Rosenthal, 2004), and has also been successfully used to quantify the lateral deviation from a straight line in walking humans (Huitema et al., 2005).

For the current study, the SDLP was used to measure the amount of lateral motion elicited as participants walked toward the aperture. Actors pass through the center of apertures and corridors by equalizing the rate of optic flow on the left and right retina (Srinivasan, Lehrer, Kirchner, & Zhang, 1991; Duchon & Warren, 2002). This suggests that a straight line path would be optimally efficient for goal-directed locomotion through an aperture. Therefore, as participants approached the aperture in the Dynamic phase, the deviation from this optimal line was used to quantify motion variability and index the spatial requirements of locomotion. Larger lateral motion variability was represented by a larger SDLP. The SDLP was calculated separately for the position of the walking device and the midpoint of the right and left shoulders.

The SDLP captures how much variation is present in a given trial by measuring the spread of observations around the mean. However, it does not measure how the time sequence impacts the data, and it does not distinguish the type of variation; it provides no information regarding the complexity, regularity, or determinism of the time-series data. For example, two trials may produce identical SDLP values, but one trial may be far more regular and predictable than the other. Predictability and complexity of variation may play an important role in the use of action-scaling to determine affordances. Therefore, in order to gain information about the sequential dependence and complexity of the lateral movements, sample entropy (SampEn) was also calculated for each trial.

SampEn quantifies the property of information generation of a time series (Kuznetsov, Bonnet, & Riley, 2014; Richman & Moorman, 2000). If a time series generates large amounts of new information (i.e., new data values and patterns of data values that have not been seen prior in the time series), this indicates a more complex and less predictable pattern of variability. Conversely, if a time series generates only small amounts of new information (i.e., data values and patterns of data values that are repetitions of earlier points in the time series), this indicates a more regular and predictable pattern of variability. Importantly, SampEn has been shown to be effective for short and noisy data sets as small as 60 data points (Pincus 1991), although 100 to 20,000 data points is more appropriate (Richman & Moorman, 200). The robustness of the Sample Entropy calculation is ideal to analyze the complexity of a single trial where a participant walks a short distance (each trial produced 180-300 data points).

CHAPTER THREE

RESULTS

Data Preparation

Extraction. Raw data was collected such that each individual trial produced a .csv file containing X, Y, and Z positional data (collected at 60 Hz) for each of the motion trackers, placed on the left and right shoulders, as well as on the walking device (where applicable). A data-extraction program was written in Python 2.7 (Python.org) that took the .csv file as input, and returned a single column .txt file containing the average X positional data for the left and right shoulder motion trackers at each measurement occasion, as well as an additional single column .txt file containing the walking device X positional data (where applicable).

De-trending and Filtering. Upon inspection of the plots of the single column .txt files, a slight positive linear trend was found. Since linear trends pose a threat to accurate calculations of the standard deviation and the Sample Entropy, a second Python program was written to de-trend the data in each file. Plots of the de-trended data revealed a sinusoidal-like wave form about the x-axis.

Next, to reduce components of noise in the final signal, the de-trended data were submitted to a filtering process. Analysis of each data file revealed a maximum stride frequency of 1 Hz (1 stride is 2 steps, so this is equivalent to 120 steps per minute). As suggested by Winter (2005), biomechanical movement data with a fundamental frequency of 1Hz was subjected to a low-pass Butterworth filter normalized with respect to a cutoff frequency of 6 Hz. This filter resulted in a 90 degree phase lag, so the same filter was run in the reverse direction of time to return the filtered data to be in phase with the raw data. The entire filtering process was written and completed within a Python program.

Computing Motion Variability. For each de-trended and filtered single column .txt file, the standard deviation was computed. Thus, the final data set included the Standard Deviation of the Lateral Position (SDLP) for the average of both shoulders and for the walking device. Higher SDLP values represent larger deviations from an optimal straight line path.

In order to compute SampEn, two parameters needed to be determined. Template Length (m) represents the number of consecutive data points used to define a vector, and Tolerance (r) establishes the level of exactness required in order to claim two vectors as repetitive matches. Due to the comparative nature of the analysis plan, SampEn parameters had to be kept constant across all trials (Pincus, 1991). Therefore, a subset of twenty trials were randomly selected across conditions and phases to establish parameters. For each of these trials, the SampEn algorithm was computed for a range of r and m values, and then SampEn was plotted as a function of r for several values of m (Ramdani et al., 2009). The template length (m) parameter was chosen as the first value at which different curves first converge. In a second plot, the relative error for SampEn was plotted as a function of r for the selected value of m. The Tolerance (r) parameter was chosen as the value at which relative error was minimized. The parameter values to be used in the full data set were selected by taking an average of the calculated parameters. With the selected parameters m and r, Sample Entropy was computed for each trial using a batch code executable function in MatLab (Mathworks.com). Higher values of SampEn represent higher complexity in the patterns of variation.

Testing for normality. Prior to analyses, all continuous outcome variables were plotted and tested for normality. It was found that the SDLP and SampEn variables for the shoulders as well as the walking devices were considerably skewed. Each of these four variables were submitted to a logarithm transformation in order to normalize their distribution.

Outlier analysis. For each analysis, residuals were obtained from the full model, and then standardized. The standardized residuals were plotted and then inspected for overly influential cases that fell outside of a normal distribution (Cohen, Cohen, West, & Aiken, 2003). Selected outliers were removed from the dataset. In all of the analyses, it was found that <1% of the trials were removed due to outliers.

Binary Logistic Regression

The use of a dichotomous dependent variable (judgment: yes or no) produced a nonlinear cubic distribution. Since nonlinearity violates an assumption of linear regression, the raw scores needed to be transformed into a linear distribution. By using a binary logistic regression (Peng, Lee, & Ingersoll, 2002), the regression model will predict the linear logit value, which can later be transformed into a probability score.

Values on the cubic distribution represent probability scores, which range from 0 to 1. Dividing the probability of an event occurring by the probability of an event not occurring will calculate the odds ratio of an event, which produces a quadratic distribution. Lastly, the logarithm of the odds ratio will produce the logit value, which produces a linear distribution. Thus, analyses requiring linear regression will utilize the logit values, and the results will be converted back to an odds ratio for meaningful interpretation.

To interpret the effects of continuous variables in a logistic regression, the regression coefficient is converted into an odds ratio which has a quadratic trend. For example, a probability of .5 is represented by an odds ratio of 1:1. Instead of having an additive effect on the dependent variable, the odds coefficient has a multiplicative effect (i.e., a one-unit increase in the predictor results in the odds ratio being *multiplied* by the odds coefficient).

Hierarchical Linear Modeling

Due to the repeated measures design of the experiment, variables had considerable nesting. That is, since each participant completed 126 trials, a portion of the variance in their responses can be attributed to a common source – the fact that the same participant was responding to each trial. This, along with other manipulated within-participant factors, created multiple levels of variance. In a mixed model regression, Level 1 (within-participant) variables represent those that change from trial to trial (for this study: door width, phase, and motion variability). Level 1 variables explain residual variance from the regression line, indicated by the difference between actual and predicted values for each trial. Level 2 (between-participant) variables represent those that change from participant to participant (for this study: condition, shoulder width, and aggregated motion variability). Level 2 variables explain intercept variance, indicated by the difference between the overall regression intercept and the intercepts of each participant's individual regression equation. Level 1 by Level 2 interactions occur when within-participant effects are moderated by between-participant variables. These cross-level interactions explain slope variance, indicated by the difference between the overall regression slope and the slope of each participant's individual regression line. In order to properly account for variance at each level, Hierarchical Linear Modeling (HLM) was used (Hoffman, 1997).

When using hierarchical linear modeling, it is important to hold the regression coefficient of the intercept constant across all models. In order to do this, all continuous variables were grand-mean centered. Thus, the intercept coefficient of the regression equation represents the predicted outcome when all continuous variables are held at their average.

A conservative model was implemented to minimize the likelihood of spurious results from the analyses. For each analysis, an initial main effects model was run, such that all main effects (Level 1 and Level 2) were included in the analysis at once. Results for each of these main effects is reported from the initial main effects model. Next, to analyze the interactions, individual interaction terms were added to the main effects model one at a time. In each iteration of the model, there was never more than one interaction present at a time. That is, interaction A was included with the main effects model to gather the results for interaction A, then interaction A was removed from the model and interaction B was included with the main effects model, and so on. Results of each interaction are reported from the model in which that interaction was included.

Effect sizes for each fixed effect will be presented as the change in R^2 (proportion of explained variance) comparing the model that includes the fixed effect and that same model with the fixed effect removed. The resulting sr^2 can be interpreted as the percentage of variance accounted for by the fixed effect. For a dichotomous dependent variable in a hierarchical linear model, the R^2 is calculated by taking the ratio of explained variance to total variance (Snijders & Bosker, 2012). Explained variance is calculated as the variance of the predicted logit values. Total variance is the sum of the predicted logit variance, the intercept variance (unexplained variance at Level 2), and the residual variance (unexplained variance at Level 1, denoted by a constant value of 3.29). Thus, the R^2 will be calculated using the equation below:

$$R^2 = \frac{predicted\ logit\ variance}{predicted\ logit\ variance + intercept\ variance + 3.29}$$

Preliminary Analyses. As previously mentioned, it was expected that the various walker types would provide differences in both frontal dimension (to facilitate analyses that reveal body-scaling) and motion variability (to facilitate analyses that reveal action-scaling). Prior to running the main analyses, a series of one-way ANOVAs were conducted to see if there were differences in the motion variability scores across conditions. There was a significant effect of condition on Shoulder SDLP (F (3, 1626) = 7.29, $p < 0.001$), such that the control condition had significantly lower values of shoulder SDLP than any other condition, see Figure 3.1. Additionally, there was a significant effect of condition on Shoulder sample entropy (F (3, 1608) = 87.8, $p < 0.001$), such that there was a steady and significant increase in shoulder SampEn values in the following order: Standard walker (lowest), wheeled walker, cane, control (highest), see Figure 3.2.

One-way ANOVAs were run to see if there were differences in walker motion variability in the three walker conditions. There was a significant effect of condition on Walker SDLP (F (2, 1207) = 17.76, $p < 0.001$), such that the wheeled walker had higher SDLP values than the standard walker and the cane condition, see Figure 3.1. Lastly, there was a significant effect of condition on Walker sample entropy (F (2, 1186) = 145.03, $p < 0.001$), such that there was a steady and significant increase in walker SampEn values in the following order: Standard Walker, Cane, Wheeled Walker, see Figure 3.2.

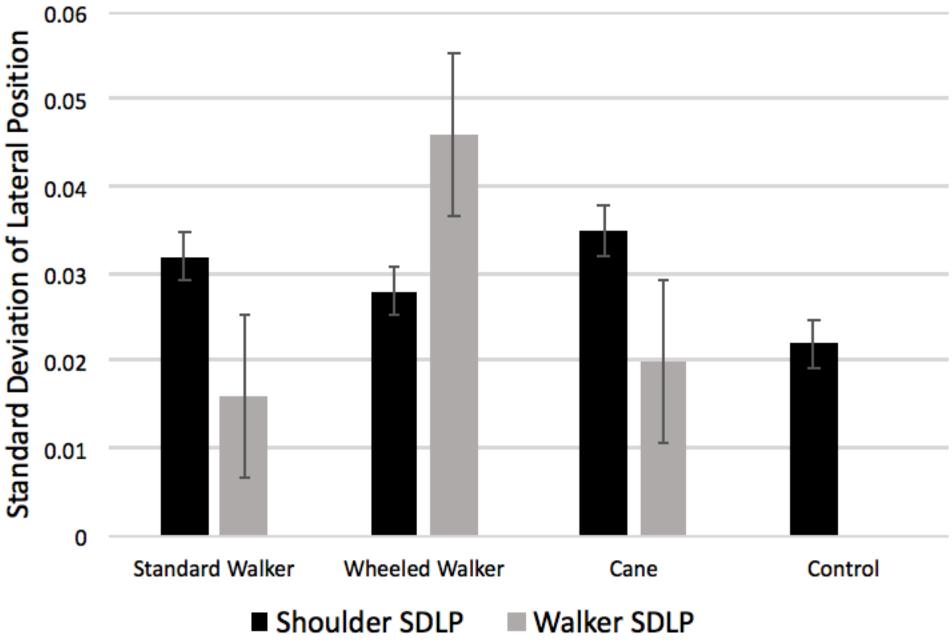

Figure 3.1. Average Shoulder and Walker SDLP by Condition. Error bars represent +/- 1 standard error.

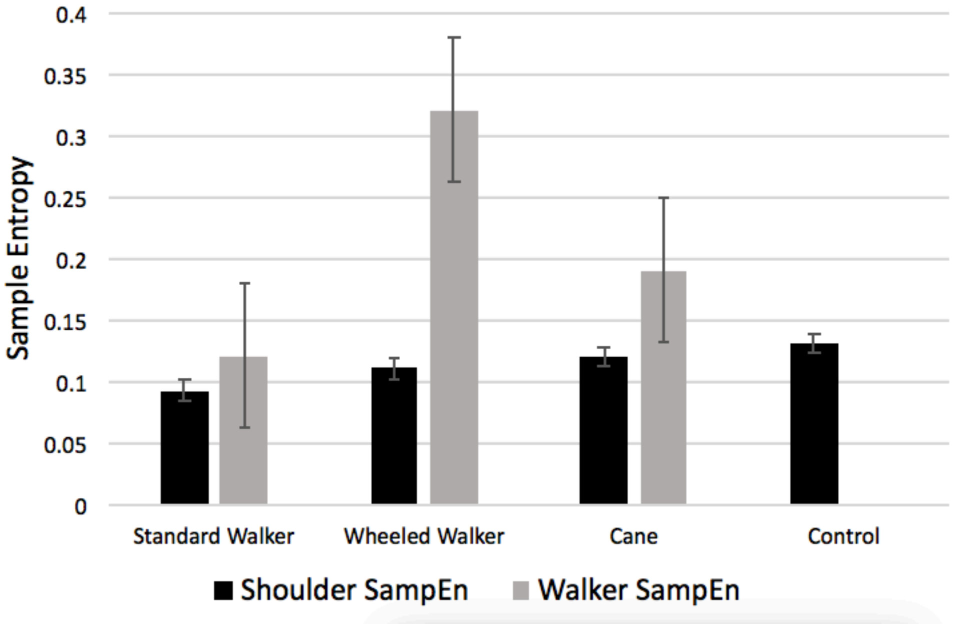

Figure 3.2. Average Shoulder and Walker SampEn by Condition. Error bars represent +/- 1 standard error.

Predicting Passability Judgments

Model 1. First, the entire data set was included in the model to assess the effects of condition, phase, and aggregated motion variability on the likelihood that a participant judged the doorway to be passable. See Table 3.1 for the results of the omnibus *F* test. Overall, this model accounted for 59% of the variance in judgment.

As expected, condition was a significant predictor of passability judgments (F (3, 30)= 12.18, $p < 0.001$). Post hoc pairwise comparisons showed that – holding all other variables at their average – participants in the control condition were significantly more likely to judge a door as passable compared to participants in the standard walker condition (t (30) = 12.25, p <0.001) and wheeled walker condition (t (30) = 16.98, p <

0.001). Similarly, participants in the cane condition were significantly more likely to judge a door as passable compared to participants in the standard walker condition (*t* (30) = 13.68, *p* <0.001) and the wheeled walker condition (*t* (30) = 18.29, *p* <0.001). There was no difference in the likelihood of making a passable judgment between the cane and control conditions (*t* (30) = 0.25, *p* = 0.801), or between the standard walker and wheeled walker conditions (*t* (30) = 0.12, *p* = .903, see Table 3.2).

Table 3.1

Omnibus F test results for fixed effects predicting passable judgments in Model 1

Predictor	df1	df2	F	sr^2
Trial	1	4899	4.84*	<0.001
Phase	2	4899	27.19***	0.02
Door width	1	4899	760.27***	0.41
Condition	3	30	12.18***	0.15
Shoulder width	1	30	1.42	--
L2 Shoulder SDLP	1	29	1.13	--
L2 Shoulder SampEn	1	29	0.07	--
Shoulder width * Condition	3	27	4.11*	0.05
Doorwidth * Shoulder width	1	4898	0.43	--
Doorwidth * Condition	3	4896	2.52	--
Phase * Condition	6	4839	2.26*	0.02
Phase * L2 Shoulder SDLP	2	4897	9.18***	<0.001
Phase * L2 Shoulder SampEn	2	4897	4.51*	<0.001

note: * p < .05, ** p < .01, *** p< .001

Figure 3.3 plots the probability of judging a doorway to be passable by condition. The door width at which participants have a .5 probability of making a passable judgment represents the perceived critical passability width, which is the largest door width that participants perceive they can pass through (Stevens, 1986). On the left graph, probability scores are plotted against door width (cm), and there are visible differences in perceived critical boundaries between conditions. On the right graph, probabilities are plotted against a dimensionless ratio between the width of the door and the participant's widest frontal dimension (shoulder width for the control/cane conditions, walker width for the standard/wheeled walker conditions). Once plotted to account for the scaling of the person-plus-object system, differences by condition were eliminated. See Table 3.2 for critical widths and critical ratios by condition. The effect of condition accounted for 15% of the explained variance in the model.

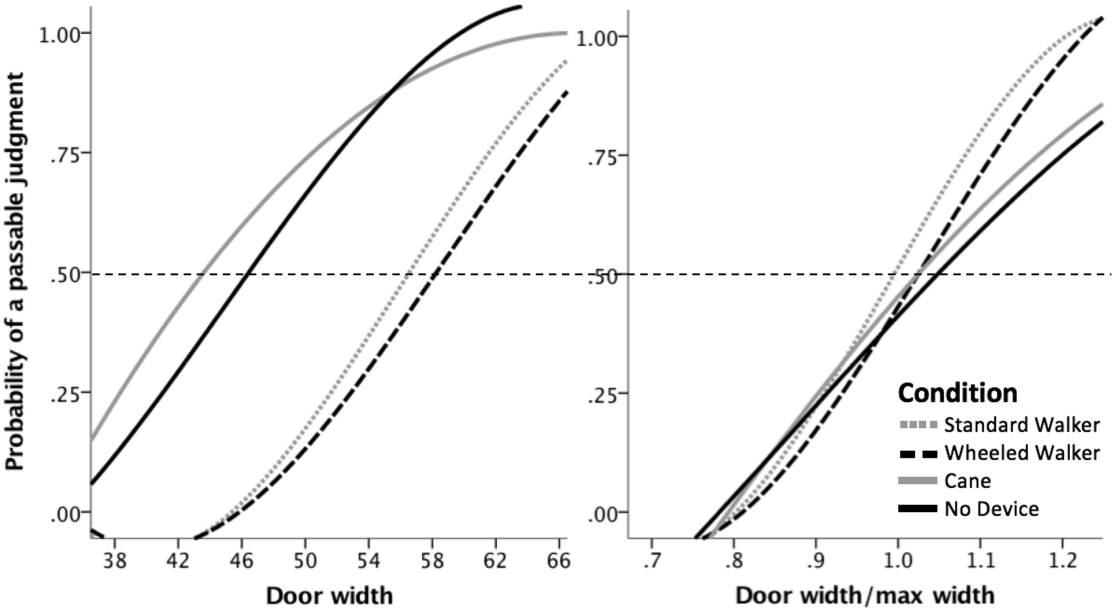

Figure 3.3. Plot of the probabilities of making a passable judgment by Condition. On left: probabilities are plotted against door width (cm). On right: probabilities are plotted against a dimensionless ratio (pi-value).

Table 3.2

Differences in passability judgments across Conditions in Model 1

Condition	Prob. passable judgment (SE)	Critical Width (cm)	Critical Ratio
Standard Walker	0.06 (0.06)	57	0.96
Wheeled Walker	0.05 (0.05)	59	1.01
Cane	0.98 (0.02)	44	1.01
Control	0.98 (0.03)	46	1.05

note: probabilities are based on a 53 cm door width, and are averaged across all phases

Additionally, there was a significant main effect of phase (*F* (2, 4899) = 27.19, *p* <0.001). Post hoc pairwise comparisons revealed that – holding all other variables at their average – the probability of a participant judging a doorway to be passable was significantly lower in the Dynamic phase compared to the second Static phase (*t* (1610) = 4.94, *p* <0.001) and the first Static phase (*t* (1610) = 6.87, *p* < 0.001). Additionally, the probability of a participant judging a doorway to be passable was significantly lower in the second Static phase compared to the first Static phase (*t* (1610) = 2.42, *p* = 0.01, see Table 3.3).

Table 3.3

Differences in passability judgments across Phases

Phase	Prob. passable judgment (SE)	Critical Width (cm)	Critical Ratio
Static 1	0.72 (0.09)	50	0.99
Dynamic	0.43 (0.11)	54	1.05
Static 2	0.63 (0.10)	52	1.02

note: probabilities are based on a 53 cm door width, and averaged across conditions

Results of the F test revealed a significant interaction between phase and condition (F (6, 4839) = 2.26, $p < 0.05$). The significant omnibus test justified further post-hoc investigations. The file was split by condition to assess the simple effects of phase. Results showed the Dynamic phase reduced the probability of judging a door as passable compared to the First Static phase for the Standard Walker ($p < 0.001$), Wheeled Walker ($p < 0.001$), and Cane condition ($p = 0.003$). However, there was no difference between the first Static Phase and the Dynamic phase in the Control condition. See Figure 3.4 and 3.5 for the general pattern of the interaction, which shows that the Standard Walker, Wheeled Walker, and Cane conditions were more affected by phase than the Control condition.

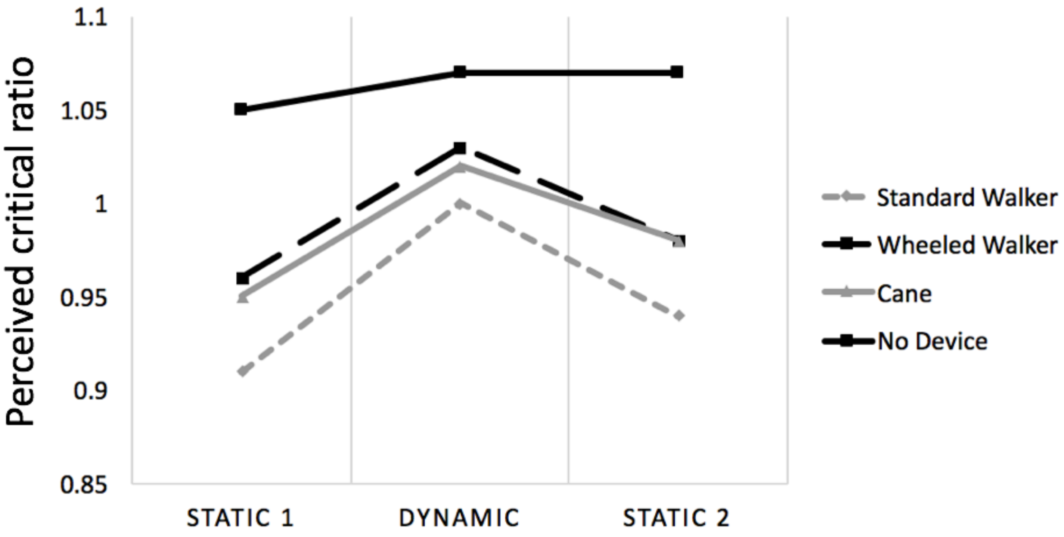

Figure 3.4. Perceived critical passability ratio by Phase and Condition. Perceived critical ratio represents the smallest door width that participants judged as passable, in units of the participant's largest frontal dimension (e.g., ratio = 1 indicates that the door width was equal to the widest dimension).

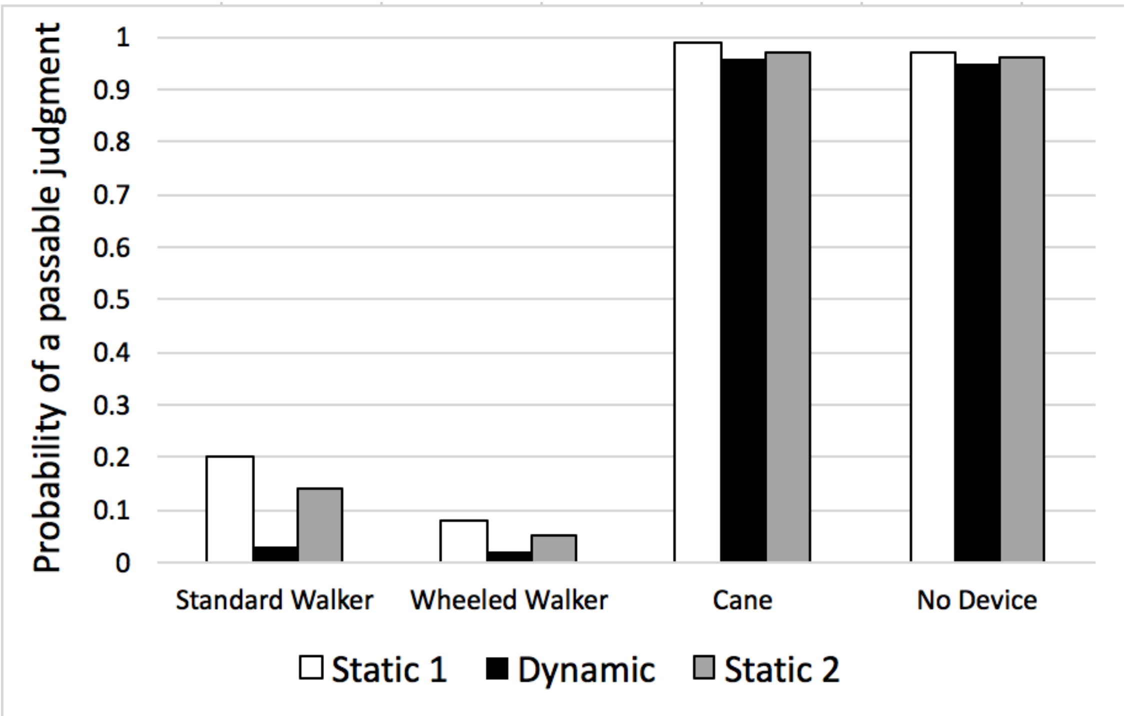

Figure 3.5. Probability of making a passable judgment by Phase and Condition. Probabilities were calculated for a 53 cm door width.

In addition to the effects of categorical variables on passability judgments, there were several significant continuous predictors (See Table 3.4 for regression coefficients). Recall that in a binary logistic regression, the odds ratio is a multiplicative, rather than additive, factor on the dependent variable. There was a significant main effect of trial, such that as the trials within a given phase increased, the odds of judging a door to be passable improved by a multiplicative factor of 1.02. Tests of the simple slopes revealed that this effect was only present in the First Static Phase, but not the Dynamic or Second Static Phase (see Table 3.5). Additionally, door width was a significant predictor of passability judgments, such that as the door width increased by 1cm, the odds of judging the door to be passable were 1.82 times higher.

Table 3.4

Fixed coefficients and standard errors for Model 1 predicting passable judgments

Fixed Effects			
Predictors	Coefficients (SE)	t	odds ratio
Intercept	3.945	--	--
Trial	0.02 (0.01)	2.20*	1.02
Doorwidth	0.60 (0.03)	20.99***	1.82
Shoulder width	-0.19 (0.16)	-1.19	--
L2 Shoulder SDLP	5.38 (5.06)	1.06	--
L2 Shoulder SampEn	1.68 (6.16)	0.79	--

note: * p < .05, ** p < .01, *** p< .001

Table 3.5

Simple slopes of Trial by Phase

Phase	Coefficients (SE)	t
Static 1	0.03 (0.01)	3.14**
Dynamic	0.002 (0.01)	0.22
Static 2	0.015 (0.012)	1.29

note: * p < .05, ** p < .01, *** p< .001

Shoulder width was not a significant predictor of passability judgments. However, when moderated by condition, shoulder width became a significant predictor of passability judgments. Analysis of the simple slopes revealed no effect of shoulder width for participants using the standard walker (*B* = -0.038, *Std. Error* = 0.18) or the wheeled walker (*B* = -0.026, *Std. Error* = 0.11). In other words, when participants used a standard walker or a wheeled walker, the simple slopes were no different from zero. However, the effect of shoulder width was present for the cane condition (*B* = -1.003, *Std. Error* = 0.12 *odds ratio* = 0.37) and the control condition (*B* = -0.701, *Std. Error* = 0.21, *odds ratio* = 0.49). A 1cm increase in the participant's shoulder width reduced the odds of judging a door to be passable by a multiplicative factor of 0.37 and 0.49, respectively, see Figure 3.6. The unique effect of this interaction accounted for 5% of the explained variance.

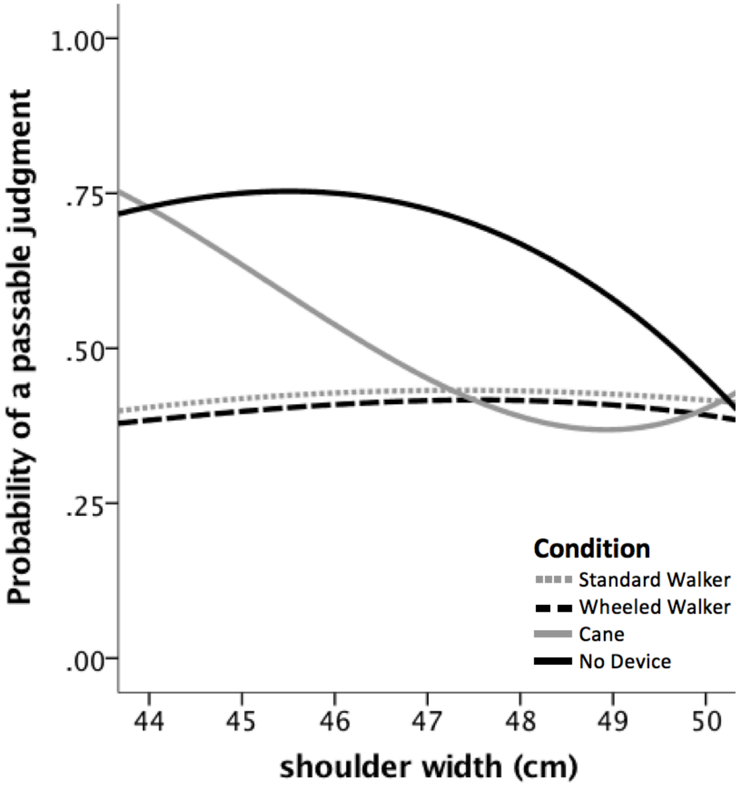

Figure 3.6. Probability of making a passable judgment plotted against Shoulder width and grouped by Condition.

To assess the effects of a participant's overall motion variability on passability judgments, SDLP and SampEn of the shoulder were aggregated to each participant and included in the model as a Level 2 predictor. Neither L2 SDLP nor SampEn were significant predictors of passability judgments. However, the omnibus F test revealed significant aggregated Shoulder SDLP * Phase and Shoulder SampEn * Phase interactions. The file was split by phase and regression coefficients were computed to show the effect of L2 Shoulder SDLP and L2 Shoulder SampEn on each phase individually. A test of the simple slopes revealed that the effect of L2 SDPL and SampEn were different across phases (see Table 3.6). Although the simple slopes differed from each other, they did not differ from zero.

Table 3.6

Simple slopes of Aggregated Motion Variability by Phase

	L2 Shoulder SDLP			L2 Shoulder SampEn		
Phase	Coefficients (SE)	odds ratio	t	Coefficients (SE)	odds ratio	t
Static 1	6.9 (4.21)	992.27	1.67	2.11 (5.02)	8.24	0.46
Dynamic	1.96 (4.53)	7.09	0.44	0.83 (5.48)	2.29	0.19
Static 2	0.12 (6.42)	1.12	0.03	-3.89 (7.62)	0.02	0.54

note: * p < .05, ** p < .01, *** p< .001

Model 2. Next, only the data from the Dynamic phase was analyzed in order to assess the effects of trial by trial shoulder motion variability on the likelihood of judging a doorway to be passable. Since participants only walked towards the door in the Dynamic phase, only these trials have data for shoulder motion variability. Analyzing only these trials allows the use of shoulder motion variability as a level 1 predictor. See Table 3.7 for the results of the omnibus *F* test.

Table 3.7

Omnibus F test results for fixed effects predicting passable judgments in Model 2

Predictor	df1	df2	F	sr^2
Trial	1	1598	0.9	--
Doorwidth	1	71	153.67***	0.08
Speed	1	1598	0.12	--
Shoulder SDLP	1	1598	0.05	--
Shoulder SampEn	1	1598	0.12	--
Condition	3	32	16.11***	0.21
Shoulder width	1	30	2.87	--
Condition * Shoulder SDLP	3	27	3.28*	0.03
Condition * Shoulder SampEn	3	31	2.353	--

note: * $p < .05$, ** $p < .01$, *** $p < .001$

As in the previous model, Condition was again a significant predictor of passability judgments (F (3, 32) = 16.11, $p < 0.001$). Post-hoc pairwise comparisons revealed the same pattern as above, such that participants in the cane and control condition were more likely to judge the door to be passable compared to participants in the standard walker or wheeled walker conditions. There was no difference in passability judgments between the standard walker and the wheeled walker conditions, nor between the cane and control conditions, see table 3.8.

Table 3.8

Differences in passability judgments across Conditions in the Dynamic Phase

Condition	Prob. passable judgment (SE)	Critical Width (cm)	Critical Ratio
Standard Walker	0.024 (0.03)	59	0.98
Wheeled Walker	0.015 (0.02)	59	0.98
Cane	0.986 (0.01)	43	0.98
Control	0.955 (0.05)	47	1.04

note: probabilities are based on a 53 cm door width

Also following the previous model, there was a significant effect of the door width; as the door width increased by 1cm, the odds of judging the door to be passable increased by a multiplicative factor of 1.82. However, there was no effect of Level 1 shoulder SDLP or shoulder SampEn on the probability of judging a door to be passable. That is, trial by trial motion variability was not a significant predictor of passability judgments.

To see if shoulder motion variability was moderated by condition, the interaction terms were included in the model. Results of the omnibus F test showed the effect of shoulder SDLP on passability judgments was significantly moderated by condition. A post-hoc test of the simple slopes revealed that the effect of trial by trial Shoulder SDLP on passability judgments differed by condition. While the simple slopes across conditions differed from each other, the simple slope for the control condition was the only one that significantly differed from zero. See Table 3.9 for the simple slopes and Figure 3.7 for the effect of SDLP on passability judgments across conditions.

Table 3.9

*Simple slopes for Shoulder SDLP * Condition.*

Predictors	Coefficients (SE)	t	odds ratio
Standard Walker	2.41 (4.72)	0.59	11.13
Wheeled Walker	-5.39 (3.36)	1.58	0.004
Cane	2.13 (2.39)	0.89	8.41
Control	6.96 (2.85)	2.42*	992.27

note: * p < .05, ** p < .01, *** p< .001

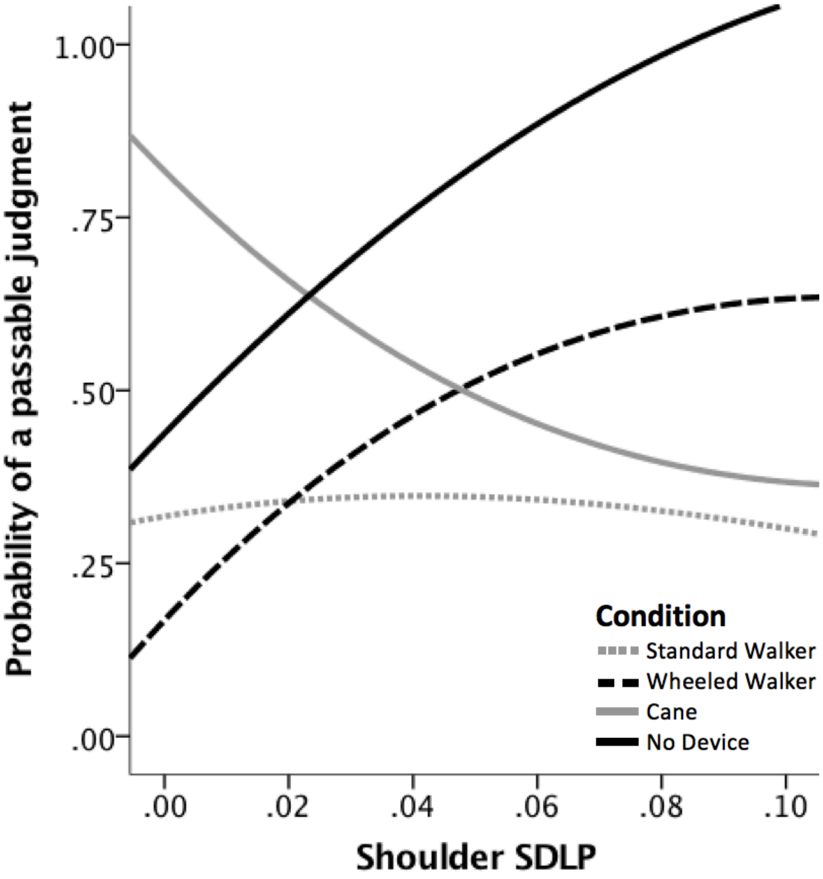

Figure 3.7. Probability of making a passable judgment plotted against Shoulder SDLP and grouped by condition. Note that raw SDLP values are included in the plot for interpretation. Only the simple slope for the control condition was significantly different from zero.

Model 3. Lastly, only the Dynamic phase data from the standard walker, wheeled walker, and cane conditions were used to assess the effects of trial by trial walker motion variability on doorway passability judgments. See Table 3.10 for results of the overall omnibus F test.

Table 3.10

Omnibus F test results for fixed effects predicting passable judgments in Model 3

Predictor	df1	df2	F	sr^2
Trial	1	1174	0.803	--
Door width	1	1122	168.38***	0.43
Walker SDLP	1	1123	1.468	--
Walker SampEn	1	1174	1.144	--
Shoulder width	2	23	2.174	--
Condition	1	19	12.59***	0.14
Condition * Walker SDLP	2	1172	0.189	--
Condition * Walker SampEn	2	1172	0.86	--

note: * $p < .05$, ** $p < .01$, *** $p < .001$

Following the results of the previous models, there was a significant main effect of Condition. Again, there was no difference in the likelihood of judging a 53 cm doorway to be passable for the standard walker ($M = 0.025$, $SE = 0.031$) and the wheeled walker ($M = 0.011$, $SE = 0.013$, $t\ (21) = 0.068$, $p = .501$). However, the cane condition ($M = 0.972$, $SE = 0.032$) was significantly more likely to judge the door as passable compared to the standard walker ($t\ (24) = 9.85$, $p < 0.001$) and the wheeled walker (t (24) = 14.78, $p < 0.001$). The effect of condition accounted for 14% of the variance in the model. Additionally, the door width was again a significant predictor of passability judgments ($B = 0.61$, *odds ratio* = 1.84, $p = 0.004$), such that larger door widths increased the likelihood of judging the door as passable. The effect of door width accounted for 43% of the variance in the model. There was no effect of the walker's SDLP or SampEn on passability judgments, nor was the effect of walker motion variability moderated by condition.

Exploratory Analysis. Due to the large range of door widths presented to each participant, door widths at each extreme (the largest and smallest widths) may have resulted in easy judgments of passability that did not require consideration of the participant's motion variability. That is, perhaps the door width was far too large or far too small for a participant to pass through, in which case they need not rely on their spatial requirements of movement to determine their passability. Because of this, an exploratory analysis was run to test if trial by trial motion variability was a predictor of passability judgments for those door widths nearest to each participant's critical boundary. Each participant's maximum frontal width was determined as the shoulder width for the cane and control conditions, and as the width of the walker for the standard and wheeled walker conditions. Then, the two presented door widths above and below each participant's maximum frontal width were selected for the analysis (n = 496 trials). This subset of the entire sample was submitted to a binary logistic hierarchical linear model predicting the likelihood of judging a doorway to be passable.

See Table 3.11 for the results of the omnibus F test. While the presented door width and condition were again significant predictors of passability judgments, trial by trial shoulder and walker motion variability (SDLP and SampEn) were not significant predictors, nor were they significantly moderated by condition.

Table 3.11

Omnibus F test results for fixed effects predicting passable judgments in Model 4

Predictor	df1	df2	F	sr^2
Trial	1	471	0.23	--
Door width	1	471	118.18***	0.39
Shoulder SDLP	1	471	0.94	--
Shoulder SampEn	1	471	1.53	--
Walker SDLP	1	335	0.05	--
Walker SampEn	1	335	0.02	--
Condition	3	32	17.66***	0.12
Shoulder width	1	27	4.08	--
Shoulder SDLP * Condition	3	468	1.99	--
Shoulder SampEn * Condition	3	468	0.99	--
Walker SDLP * Condition	2	333	0.09	--
Walker SampEn * Condition	2	333	0.98	--

note: * $p < .05$, ** $p < .01$, *** $p < .001$

CHAPTER FOUR

DISCUSSION

The goals of this experiment were threefold. First, this experiment investigated the effects of assistive walking devices on their user's perception-action system. Second, the experiment sought to compare the individual impacts of body-scaling and action-scaling on one's perception of affordances. Lastly, this experiment looked to quantify action-scaling – that is, to find a quantitative predictor of affordance perception that takes into account the actor's dynamic capabilities (similar to how a dimensionless pi-ratio takes into account the morphology of the actor). Ultimately, the quantification of body-scaling (pi-value) and action-scaling could be used together as a more accurate predictor of affordance perception.

These research questions were tested by first introducing participants to a novel form of locomotion. It was crucial that the novel form produced changes in both the morphology and dynamic properties of the user. For this reason and other relevant applications, assistive walking devices were chosen as the novel form of locomotion. Next, the novice walker users made judgments of their ability to pass through an aperture (a relevant task given their changed morphology) before producing any movement with the devices. These judgments could not have considered the new dynamic capabilities of the walking devices because participants had not yet been introduced them; Having not *used* the walking devices, the judgments from this First Static Phase must have only considered the change in morphology of the devices. Thus, judgments from this phase utilized *only* body-scaling.

Next, participants made their judgments *while* producing the task-relevant movement. By using their walkers to move towards the door prior to judging if they could pass through the door, participants could now consider the dynamic properties of their locomotion. By tuning into relevant properties of their new dynamics introduced by the walking device, participants now had the opportunity to engage in action-scaling. The change in affordance perception between the First Static Phase and the Dynamic Phase represents the impact of action-scaling above and beyond that of body-scaling for affordance perception. During this phase, motion data were captured as the participants walked towards the door. Data were collected on the relevant dynamic properties of participants' movements in order to look for patterns between those properties of locomotion and affordance judgments. Two metrics of movement were calculated from the motion data. The Standard Deviation of Lateral Position (SDLP), a purely spatial metric, was used to quantify the size of the lateral sway of each participant. Sample Entropy, a temporal-spatial metric, quantified the predictability and determinism of the lateral sway pattern over time.

After participants had made their passability judgments while walking towards the door, a Second Static Phase required participants to make their judgments again while not producing movement. This final phase allowed testing of whether engaging in movement informs later static judgments of affordances, that is, whether action-scaling information can be calibrated to and transferred to other tasks. If the Second Static Phase had similar judgments to the Dynamic Phase, this would suggest that both phases utilized both body-scaling and action-scaling.

In support of Hypothesis 1, results indicated that novice walker users successfully engaged in body scaling to the person-plus-object system. For the cane condition (in which the walking device did not extend the frontal dimension of the user) and the control condition, participants scaled their aperture passability judgments to the width of their shoulders. But for conditions in which the walking device extended the widest frontal dimension of the user (the standard and wheeled walkers), participants disregarded their shoulder widths and instead used the geometric width of the walking device to determine their passability. While there were differences in perceived critical passability width between conditions, the introduction of a dimensionless ratio between the door width and the widest frontal dimension eliminated these differences (See Figure 3.3). This finding simultaneously confirms research by Warren & Whang (1987) on body-scaling using the shoulders, as well as research by Wagman & Taylor (2005) on the person-plus-object system. While Warren (1987) found the perceived critical passability width of individuals to be 1.15 times the width of the body, the current experiment saw the control condition to determine their critical width at 1.05 times the width of the body. Meanwhile, Higuchi et al. (2004) found that novice wheelchair users estimate their perceived critical passability width as .93 times the width of the wheelchair, which is similar to the present study's findings that users of the standard walker overestimated their abilities by placing their perceived critical width at .96 times the width of the walker.

Additionally, allowing users to engage in locomotion altered their judgments of passability. Judgments were more conservative in the Dynamic Phase than in the First

Static Phase, which supports Hypothesis 2 and suggests that information from performing the task-relevant movement impacted affordance perception above and beyond that of body-scaling information alone. It was also expected that there would be a carryover effect, such that information from the Dynamic Phase would be transferred to later static judgments. Results showed that there was a partial carryover effect: judgments from the Second Static Phase fell into a middle ground, where they were more conservative than the First Static Phase, but less conservative than the Dynamic Phase. This suggests that practice and experience using the walking devices improved future judgments of passability, even when the experience was a small number of trials walking a very short distance. In other words, participants used the Dynamic phase to *recalibrate* their future body-scaled judgments in a way that would take into account their dynamic capabilities. Future work should investigate how much additional practice using the device is required to produce a full carry-over effect, and results should be used to inform the protocol for introducing novice users to their walking devices.

It is important to note that the introduction of locomotion was most impactful in the walking device conditions. In partial support of Hypothesis 3, results showed that the effect of Phase was moderated by Condition (see Figure 3.4 and 3.5). For novice users of walking devices (Standard walker, Wheeled walker, and Cane), there was a significant change in judgments between the First Static Phase and the Dynamic Phase. But for the control condition (in which walkers were well-experienced in the dynamic properties of their movements), there was little change in judgment across phases. This finding further supports the claim that dynamic movements are important for inexperienced users to understand their capabilities for action (Yu et al., 2012; Stoffregen et al., 2009; Mantel et al., 2015).

The change in passability judgments during the Dynamic Phase supports the hypothesis that action-scaling provides information for affordance perception above and beyond that provided by body-scaling. But if action-scaling were actually occurring, we would expect the calculated metrics of motion variability (SDLP and Sample Entropy) to be significant predictors of passability judgments. First, the SDLP indexes the magnitude of lateral sway produced during the movement; That is, larger SDLP values represent larger spatial requirements for movement. Imagine an actor standing on a conveyor belt that is moving directly through the center of a doorway. In this instance, the shoulder width of the participant represents the critical width for their passability. Any deviation from moving in this perfectly straight line, which would be naturally produced by lateral shoulder sway while walking, *should* increase the critical point at which an actor could pass through the doorway. Secondly, the Sample Entropy indexes the predictability of a movement pattern over time. Despite the magnitude of lateral sway produced by walking, it was hypothesized that having a more predictable lateral sway pattern would allow participants to have smaller critical judgments. Evidence for and against these hypotheses are presented below.

Evidence supporting the claim that action-scaling information was attuned to and utilized for affordance perception in the Dynamic phase includes the finding that trial-by-trial shoulder SDLP was only a predictor of dynamic judgments for the control condition, but not for the walking device conditions. This result is logical because small shoulder movements shouldn't affect the affordance of someone using a standard or wheeled walker, since the device itself is so much larger than any shoulder movements made. Just as shoulder width was not a significant predictor of passability judgments for the walker conditions, neither was the motion variability of the shoulders. However, the directionality of Shoulder SDLP predicting judgments was not expected: an increase in SDLP values (indexing larger magnitudes of sway) resulted in a higher probability of judging the door to be passable (See Figure 3.6). In trying to understand this odd finding, we must question the direction of causality; perhaps participants tailored their SDLP depending on the presented door width and its likelihood to afford passing through. It may have been the case that for very large door widths, participants recognized immediately that they could safely pass through, and produced larger SDLP values simply because their SDLP would not impact their ability to pass through the door. But for door widths closer to their critical passability, perhaps participants walked more carefully and produced smaller SDLP values in order to maximize their likelihood of being able to pass through the door. If shoulder SDLP was found to predict judgments in the control condition, it would be expected that the walker SDLP would be a predictor in the walking device conditions. However, this effect was not found. Overall, the finding that SDLP predicted judgments in the control condition is not strong support for the argument that action-scaling information was utilized.

There is additional evidence mounted against the argument that action-scaling information was utilized. First, in the Dynamic Phase, trial by trial motion variability was not a significant predictor of passability judgments. This finding was the case for motion variability values of both the shoulders and the walking devices, and fails to support Hypothesis 4. One possible explanation for this unexpected finding was that there were too many door widths with obvious passability. As just mentioned, many of the presented door widths were far too large or far too small, so much so that passability judgments could have been confidently made considering *just* the body-scaled information. Perhaps the additional information gained from action-scaling was most important for the door widths that were closest to each participants' critical boundary. To test this, an exploratory analysis was run that included only the trials in which the presented door width was within 2 increments from each participant's critical boundary. This analysis of a small and specific subset of data confirmed the results of the larger one, providing further evidence that motion variability was not an important predictor of passability judgments. Future work should shorten the increments for the presented door widths to allow for more precision around each participant's critical boundary, so that every presented door width can produce meaningful data for analysis.

In addition to the finding that trial by trial motion variability failed to predict judgments, it was also found that participants' average motion variability was not a significant predictor. By aggregating motion variability scores to each participant (a level 2 variable), it was possible to test if motion variability at a trait level was impacting passability judgments. In conjunction with this, it was expected that Level 2 motion variability would be moderated by phase, such that novice walker users would be able to use their aggregated motion variability information in the Dynamic Phase and the Second Static Phase, but not the First Static Phase, which was prior to their exposure to the dynamic properties of their movements. This was also found to not be a significant interaction, which fails to support Hypothesis 5.

A final piece of evidence against the action-scaling argument showed that there were group differences in motion variability between users of the standard walker and the wheeled walker. It was found that users of the wheeled walker had higher walker SDLP values and higher walker SampEn values compared to users of the standard walker. It was expected that the standard walker would have larger motion variability, but inspection of the positional data plots revealed that the wheeled walker produced higher values on both metrics due to the fact that there were abrupt changes in heading direction caused by the fixed wheels. Nonetheless, despite significant differences in motion-variability between these two conditions, there was no difference between them in passability judgments during the dynamic phase. Since both walking devices have the same frontal dimension, the fact that both conditions had equal passability judgments in the First Static Phase was expected. However, the difference in motion variability should have been met with differences in passability judgments during the Dynamic Phase, but was not.

With all of this evidence, we cannot confirm that action-scaling information (specific to the dynamic properties of locomotion) was the root of the change in passability judgments during the Dynamic Phase. One alternative explanation is that allowing participants to walk towards the door in the Dynamic phase provided them with additional information about their environment, which further aided their judgments of passability. As Gibson (1966) writes, “The ambient array with transformation carries more information than the same array without transformation." Along with the ecological approach's emphasis on the actor as an *active* explorer of their environment, perhaps the Static Phase restricted what information could be picked up by each participant, and this restriction was lifted once participants were able to actively walk towards the doorway in the Dynamic Phase. This alternative explanation holds merit because of the large increase in environmental information that becomes available once the actor engages in exploratory self-motion (optic flow, peering, parallax, eye-height scaling, etc).

Indeed, Mark (1987) discovered that a change to the individual's relevant physical dimensions reduced static affordance perception accuracy, but that limited amounts of experience with the changed dimensions allowed them to retune their judgments to their new action capabilities. In that experiment, participants were permitted to walk around in between static judgment trials of stair climb-ability and chair sit-on-ability. The Dynamic phase of the present experiment is somewhat equivalent, in that participants were required to walk before making their judgment (granted, in this case, the walking was task-specific). Thus, perhaps the walking trials provided additional information about the environment that further informed judgments of passability.

A second alternative explanation states that participants *were* utilizing action-scaling information during the Dynamic phase, but that information was not quantified by the SDLP or Sample Entropy. Limitations of the present study that may have reduced the ability to find motion variability-based predictors of passability judgments included the short walking path that limited the distance walked on each trial. In each trial of the

Dynamic Phase, participants only walked about 3 meters forward before making their judgment (an average of 3 step-cycles). Perhaps this distance was insufficient for participants to tune into the dynamic properties of their movements, especially since a sufficient portion of their movement may have been altered by preparing to start and stop. This short walking distance was chosen due to spatial limitations of the experimental space, but future work could allow longer walking distances in the Dynamic phase. In addition, future work could measure passability judgments while manipulating the motion variability of the individual (rather than just measuring it).

While this experiment failed to find a measurement of motion variability that quantified action-scaling, future work should investigate other quantifiers of motion in the search for one that represents action scaling and predicts passability judgments beyond body-scaling predictors. Potential candidate measures may include angular rotation of shoulder sway (Wilmut, et al., 2015), medial-lateral center-of-mass movement (Hackney & Cinelli, 2013), and approach speed. In conjunction, future work could assess specifically the segment of steps occurring directly before crossing the aperture, as motion variability may become most relevant when participants get close to the door. Additionally, it is recommended that future work also collect confidence ratings for each judgment of passability. It may be found that the action-scaling quantifiers (such as Sample Entropy) are better predictors of confidence than they are predictors of the actual judgment.

Of course, using healthy undergraduates as participants reduced the ecological validity of this study because they lacked the underlying instability that necessitates the use of a walking device. As such, their movements with the device may not have been equivalent to that of older adults or experienced walker users. Nonetheless, the sample of participants was expected to use body scaling and action scaling to determine their aperture passability. Using novices allowed for a better exploration of the function and extent of action scaling since passability judgments from the First Static phase were completely void of prior action-scaling information. This could not be obtained from a group of experienced walker users. Additionally, since younger adults tend to have more stability and less shoulder sway than older adults (Du Pasquier et al., 2003; Hackney & Cinelli, 2012), it was expected that their lateral motion variability when using a walker would be smaller than that of an older adult. Thus, it was assumed that any detected effects of action scaling within this study would likely be even larger with older adult walker users.

As an initial study, the use of a convenience sample was justified. However, future work should explore aperture passability judgments of older adults and expert walker users. In addition to determining how experts utilize body-scaling and action-scaling, testing true users of walking devices would also provide information about how they display a change in behavior at their critical boundary. While actors without assistive walking devices will turn their shoulders in order to pass through apertures at their critical width, it is unclear how expert walker users will behave (ie, will they turn their walker 90 degrees to squeeze it through the door - and thus compromise their stability - or will they avoid the aperture entirely?). This information may further inform why walker users fall and how to prevent it.

The applications for this study are important for the continued research on why walker users fall. While the morphological changes that come with tool use are relatively obvious and easy to attune to via visual and haptic cues, the change in dynamic properties are less obvious. As Jones et al. (2011) pointed out, one's ability to pass through an aperture is not constrained simply by their physical dimensions, but one must also take into account a margin of safety that is directly related to "how well the operator drives the machine," or in the case of this study, how well a user can locomote with the walker. Only through experience and practice can a new user of a walker attune to their new dynamic properties, and the consequences of failing to understand one's action capabilities include collisions with obstacles in the environment, which may lead to injuries. These consequences become more harmful and detrimental considering that the user population is that of older adults. Information from this and future studies should inform procedures and instructions for new users of assistive walking devices in order to help them achieve an appropriate level of experience for safe locomotion. This could ultimately help to prevent injurious collisions and falls.

In sum, novice walker users successfully recognize their changed frontal dimensions to make aperture passability judgments that are scaled to the size of their walker, and they extract additional information from the environment while actively using the device to make more conservative perceptual judgments. While experience using the device seems paramount to the recognition and incorporation of a margin of safety for the user's perception of passability, the underlying information that is specifically attuned to has yet to be determined, and future research should continue the search for a dynamics-based predictor of aperture passability. Nonetheless, results of the current study suggest that practice with the device via exploratory self-motion will improve the novice user’s perceptions of their affordances.

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