Recognition of Gait Impairment Evaluated Using an Artificial Gait Stimuli

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***Abstract*—This paper describes experiments to understand how well individuals can recognize an impaired walking pattern. The gait patterns are generated using a passive dynamic walker (PDW) model to allow a systematic change in gait patterns. The changed gait parameters include gait cadence, knee height asymmetry, step length and step time asymmetry, roll-over-shape (ROS) asymmetry, and knee damping asymmetry. Twenty participants rated twenty-four unimpaired and impaired walking patterns on a 7-point Likert scale. Results revealed that although a walking pattern may deviate dynamically from normal, there is a quantifiable range of gait impairments that may be dismissed as unimpaired. Particularly, we found that a knee height asymmetry range of roughly +10% (up) and -20%, could be dismissed as unimpaired. Findings show that the impairment perception of a damped knee joint can be countered by attaching a mass to the opposite lower limb.**

I. Introduction

Appearance is one of several concerns for individuals with a disability [1]. An individual may have the functional ability to walk, but it is still important for them to be perceived as normal as possible without having a distinctly different gait pattern. Further, for some individuals suffering from walking impairments, the confidence of looking unimpaired can mean extended periods of time spent walking and staying active in public. In this research we investigate the external perception of human gaits that deviate from an unimpaired walking pattern. We focus on the motions that constitute the gait and how to reduce the perception of gait impairment.

Results from our study could guide physical therapists in their treatments and would benefit individuals with disabilities that affect gait by determining the walking patterns that minimize the perception that their gait is impaired. In addition, prosthetists may utilize impairment perception thresholds to design and fabricate prosthetics that are geometrically different to positively augment gait dynamics, but would not be recognized as impaired by onlookers.

Our hypothesis is that gait can appear unimpaired even when it deviates from perfect temporal and spatial symmetry. Although walking with a badly sprained ankle is quickly noticed as an asymmetric limping gait, slight deviations from gait symmetry may not be recognizable by others. Similarly, an amputee wearing a transfemoral prosthetic with a knee joint located 50% up their thigh would be noticeable, however a knee joint 5% higher from the natural knee location may not be recognizable. Such room for unnoticeable variation may provide valuable rehabilitation thresholds for physical therapists or loosen design constraints for prosthetists.

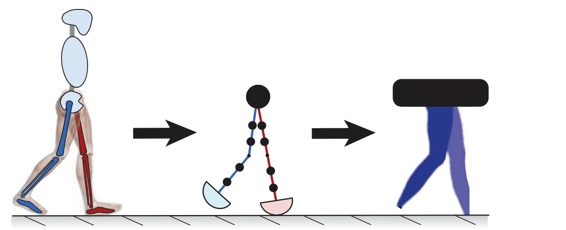

Fig. 1. The human lower limb model presented to participants was modeled with a PDW to move naturally while being carefully depicted to look like normal human limbs.

In order to systematically evaluate the perception of such deviations from normal human gait and quantify the relationship between impairment and perception, we use a purely computational passive dynamic walking (PDW) model (Figure 1) to simulate a variety of unimpaired and impaired walking patterns. These mathematically generated walking patterns are presented to individuals to be rated based on their deviation form normal walking. A purely dynamics-based computational model was used in order to precisely quantify gait impairments and draw direct links to impairment perception. Evaluated deviations from normal walking included the change in gait cadence, knee height symmetry, step length and time symmetry, roll-over-shape symmetry, and knee damping symmetry.

II. Background

Normal walking in healthy and unimpaired individuals is smooth and combines complex balancing, shock absorbing, and propelling dynamics along with central nervous system signals to generate efficient locomotion. The repeating gait cycle can be subdivided into two periods (stance and swing) [2]. Subdivisions of normal and symmetric gait can be seen in Figure 2. Deviations from normal gait, or gait impairment, can come in various forms such as deformity, muscle weakness, sensory loss, pain, and impaired motor control caused by disease, injury, or genetic birth traits [2]. Such gait pathologies can cause mild or severe deviations of gait dynamics, which may or may not be easily recognizable by other individuals. Deviations from normal walking are also often accompanied by compensatory leg dynamics, which may be damaging to other parts of the body. For instance, a person wearing a leg prosthetic, which is geometrically identical to the opposite healthy limb, may exhibit recognizable compensatory dynamics such as asymmetric step length, swing time, internal force, or foot roll-over shape [3], [4].

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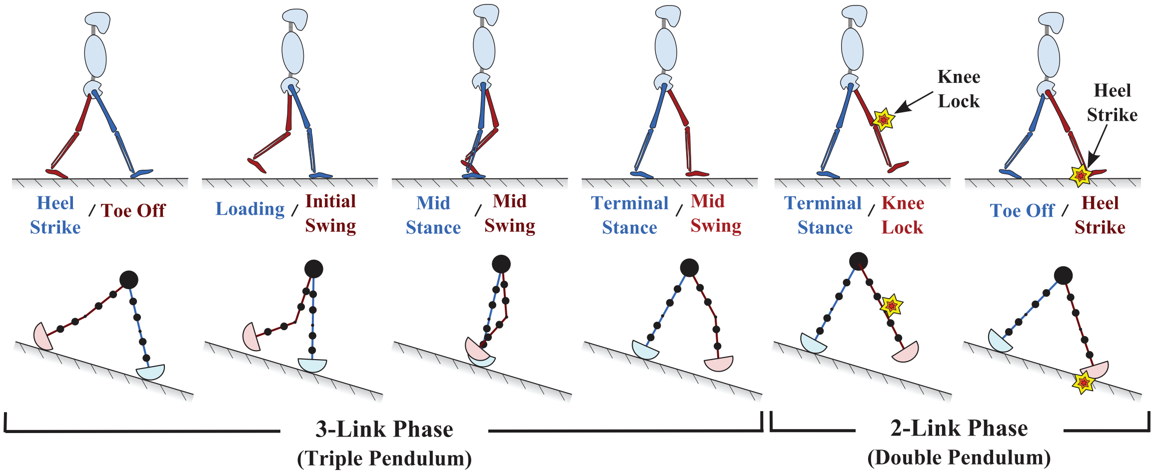

Fig. 2. (Top) Unimpaired human walking. (Bottom) Passive dynamic walking computational model used in this study to generate various walking patterns.

An important aspect of human gait is the foot roll-over shape (ROS), which is the effective shape that the foot follows during the stance phase of the gait cycle. ROS for healthy humans can be approximated to be a constant radius of one-third leg length [5], [6]. ROS have enormous effects on gait kinematics, kinetics, and balance [7], and ROS are important in prosthetic design [8], [4]. The forces exerted on a foot or by a prosthetic leg onto an individual can be manipulated if the ROS is modified properly.

In healthy humans, the two sides of the body are mostly symmetric with regards to mass and strength; thus, it makes biomechanical sense to have both knees at the same location. However, when wearing a transfemoral prosthesis (above knee), the mass and strength of the two legs are no longer equal and the biomechanical reasons to keep the same prosthetic knee location no longer exist. Moving the knee location adds a degree of freedom in the prosthesis design process that allows the gait dynamics to be adjusted [9]. However, changing the knee location depends on the answer to an essential question for this study: what amount of knee location asymmetry can be considered normal or human-like by an external observer? Note that we are only concerned with the bio-mechanical movements of leg limbs and how these movements are perceived by observers. We are not investigating the effects of limb thickness or texture perception, such as wearing a Flex-Foot Cheetah prosthetic blade foot [10].

The determination of the impairment of human kinematics is a fundamental trait. Humans are very effective at recognizing other humans and the complex motions exerted by other humans [11]. Further, humans are keenly aware of walking motions that are close to unimpaired, but are not exactly the same motions as a healthy human. To other human observers, an unimpaired gait does not draw any attention and is usually dismissed as ordinary. However, as normal and healthy walking becomes unhealthy or impaired, it starts to become more noticeable. At an extreme end, gait abnormalities can be noticed in extremely walking-impaired individuals suffering from neurological movement disorders such as athetoid cerebral palsy or dystonia, resulting in involuntary muscle contractions, repetitive movements, or abnormal postures. Even smaller changes from normal healthy gait may be easily recognizable and viewed as impaired or unfamiliar. Pathological gait, such as a slightly limping leg or sprained ankle, can be viewed as impaired, yet a larger impairment will be quickly identified.

A healthy human body with a human-like shape and movements is perceived as normal, healthy, and familiar. However, human-like objects, models, robots, or dolls often are designed to mimic normal human body parts, motions, or gestures that almost look normal, but cause an eerie feeling. This psychological reaction to the almost human-like is known as the uncanny valley [12]. The uncanny valley can be described as the perception of something that is familiar, yet incongruous, creating a repulsive effect. However, human walking movements performed by human-like characters will not cause any dip in familiarity with increased human likeness [13]. Other studies indicated similar results when walking motion parameter changes (e.g., joint dis-articulation, jerk, and phase movement changes) are examined [14][15]. In light of the above literature, the research presented here does not consider the uncanniness of deviations in gait dynamics.

While external perceptions of gait have been generally studied [16], the method of creating the gait perception stimuli has varied. By walking on an asymmetric split-belt treadmill, it has also been shown that humans are able to recognize gait asymmetry in their own gait when the walking asymmetry exceeded a specific threshold [17]. The gait parameter that corresponded the most with belt speed asymmetry was found to be stance time. While other forms of methods to recreate human motion for perception analysis has been studied in the past such as the animation of biological motion [18], motion capture [19], or morphing of bipedal locomotion movements [20], none of these use a purely dynamics-based model to evaluate the perception of human gait. Our study uses a modeled passive dynamic walker (PDW) model as a perception stimuli by systematically altering the model's dynamics by manipulating its parameters. A PDW was found to show very similar dynamically stable passive dynamics compared to slow-walking humans [21], [22]. PDW gait is shown to be kinematically and kinetically similar to human gait [6], [22], [23]. As opposed to statically stable robots such as the Honda's ASIMO and Aldebaran Robotics's NAO, dynamically stable walking robots such as a PDW, exhibit a more fluent and human-like gait. A PDW is a biped walking robot that walks down a decline with gravitational energy as its only source of power and with no active feedback [5]. While PDWs can be used to recreate and analyze normal and pathological human walking patterns, they can also be effectively utilized to study the effects on gait caused by quantitatively manipulating swinging limb parameters such as leg lengths, leg masses, joint stiffness, or foot shape parameters [24].

III. Experimental Setup

A. Experimental Protocol

Twenty individuals, 14 males and 6 females, aged 24.6±4.7, participated in this study. No participants reported having visual impairments of any type. No participants were familiar with the presented walking model or study. All participants reviewed and agreed to an approved minimal risk Institutional Review Board (IRB) consent form prior to participation. Participants were asked to rate their perception of videos presented to them. The presented videos are described in Section III-C.

Initially participants were instructed to observe and examine the normal gait for as long as they chose. They were told that this is a normal walking pattern. After that, participants were shown 24 videos (including normal walking) (Table I) in a random order for each subject. While watching each walking video, participants completed two sections for that video. The first was a subjective open-ended question asking *"What (if anything) do you think is wrong/odd/imparired/unhealthy with this walk?"*. The second section asked the participants to discreetly compare the current video with the previously observed normal walking gait on a symmetric seven point Likert scale [25], asking *"How unimpaired or impaired is this walk?"*. To judge the presented videos, the participants were given seven options ranging from *"Very Unimpaired"* to *"Very Impaired"*. The participants were given as much time as they wanted to evaluate each video that repeatedly cycled from beginning to end. The duration of all the videos was roughly thirty seconds long, however varied slightly in length depending on the gait speed.

If participants rated two videos with equivalent scores within a category, participants further evaluated these two walking videos against each other. In this second part, the two walking videos were shown simultaneously to the participants asking *"Between the two walking models, which one is more normal/unimpaired/healthy?"*. The video selected as more human-like gains 0.5 Likert points, while the other loses 0.5 Likert points. This is done to differentiate between videos and impose a rank among the data.

The PDW model depicted in each video repeatedly walked across a 50 centimeter (20 inch) wide computer monitor sitting approximatively 60 centimeters (24 inches) away and at eye-level in front of the participant. During the second part of the experiment, two videos repeatedly played on two separate computer monitors.

B. Passive Dynamic Walking (PDW) Gait Model

This study uses a PDW model because this model is repeatable, precise, and can be systematically altered in order to change gait patterns. This consistency allows the controlled variation of desired parameters (i.e., step length, limb mass, joint stiffness, ROS) without the inconsistency of human sensorimotor control under the same walking conditions.

Our PDW model is a planar nine-mass multi-pendulum system with constant-radius-shaped feet. That is, it represents an anthropomorphically correct walking human from the waist down and viewed from a two dimensional sagital plane. PDW masses are represented as one hip mass and two masses per each thigh and shank. The PDW model also rolls over a constant radius roll-over shape just as a walking human would. Just as in a human gait, the PDW legs progress through two distinct phases, stance and swing, as it advances down a decline as seen in Figure 2. During a step and before knee lock, the PDW is modeled as an inverted triple pendulum as the shank swings forward, after which it turns into an inverted double pendulum. The mathematical modeling for our PDW can be reviewed in [24] and [5]. Our biped model walks down a slope of $3.5°$ for all gait variations presented in this study. We specified the PDW thigh length, shank length, mass and mass distributions according to widely surveyed anthropomorphic body segment data [26]. The roll-over shape for normal walking was taken to be one-third leg length as found in [6]. All PDW deviations presented in this study were stable for at least fifty strides.

The displayed PDW model closely depicts the aesthetics of a person walking when viewed from the side (silhouette). The visible PDW animation sagittal view silhouette was closely illustrated to mimic human muscles, joints, knees, and feet by considering waist, mid-thigh, and max calf circumference as outlined by the United States Department of Health and Human Services Health Statistics report [27]. This aesthetic transformation of our PDW model can be seen in Figure 1. Note that the focus of this study is on the gait motions and not the appearance of the legs. Although the PDW walks down a decline, it was rotated to look as if it is walking level.

C. Passive Dynamic Walking (PDW) Model Videos

Various PDW walking parameters were computationally and systematically varied to deliberately deviate from familiar and human-like (normal) gait to explore the perception of impaired human gait. Although the PDW computational model can simulate many parameters with any parameter resolution, that would yield many videos to be judged by participants, which would result in a prolonged experiment per participant. Table I shows the different parameter categories chosen for this study that were presented to the participants. All PDW leg variations were applied to the leg closest to the observer (i.e. darker, right). Equation 1 is used to define percent asymmetry between two parameters.

$$Asymmetry\ (\%) = \left(\frac{Left - Right}{(Left + Right)/2} \right) \tag{1}$$

The following videos were presented to participants. Participants judged all videos on the the basis of gait impairment. These videos are included as a supplement along with this manuscript.

TABLE I. FIVE PDW PARAMETER CATEGORIES WERE PRESENTED, 23 LISTED HERE, PLUS A PDW MODELED NORMAL VIDEO.

Gait Cadence	Knee Height Asymmetry	Spatial and Temporal Asymmetry	ROS Asymmetry	Knee Damping with Mass Asymmetry
- 50%	+ 83%	5% (LaTa)	29%	0%
- 25%	+ 57%	13% (LsTa)	66%	40%
+ 25%	+ 22%	5% (LaTs)	100%	100%
+ 50%	- 26%	13% (LaTs)		118%
	- 40%	5% (LaTa)		
	- 61%	13% (LaTa)		

L = Step Length, T = Swing Time, s = Symmetry, a = Asymmetry

1) PDW Modeled Normal Gait: The normal PDW modeled walking pattern was symmetric, where the normal gait walking cadence was matched to that of an average healthy adult walking cadence at 110 steps/minute [2]. This video was used as the stimulus (base) for comparison in each category.

2) Gait Cadence: Gait cadence may affect the observer's perception of the gait. Four different videos of the PDW modeled normal gait at four different speeds were included (two slower and two faster) (-50%, -25%, +25%, +50%).

3) Knee Height: As previously reviewed in the background section, prosthetic knee location (knee height) may be altered in order to gain spatial, temporal, or kinetic symmetry while walking. These alterations aim to determine how much knee height asymmetry is perceived as impaired. As listed in Table I, we present three videos where the walking model has a knee asymmetry with one knee raised and three videos that show the walking model with knee asymmetry by lowering one knee. All models in this category have symmetric step lengths and swing times. Because the knee is displaced very close to the hip, the video with +83% knee height shows no knee, as seen in Figure 3, but is seen in the other videos. Knee heights are not evenly distributed from symmetric knee position because equal changes did not yield a stable PDW.

4) Spatial and Temporal Asymmetry: In this video set, our intent is to examine if spatial and temporal asymmetries such as caused by limping, partial leg paralysis (hemiplegia), or a leg prosthesis will be noticeable, that is, viewed as impaired. In two videos, step length is held symmetric while swing time asymmetry is created (LsTa); in two videos, swing time is held symmetric while step length asymmetry is created (LaTs), and in another two videos, equal amounts of step length and swing time asymmetries were created (LaTa).

5) ROS Asymmetry: Walking impairment and some prosthetics can cause asymmetries in foot roll-over shape (ROS). We included three different walking patterns with asymmetric ROS foot curves. At no ROS asymmetry, both ROS are 1/3 meter (1.09 feet) in radius, whereas at 100% ROS asymmetry the left ROS is 1/3 meters (1.09 feet) while the right ROS is 0.111 meters (0.36 feet).

6) Knee Damping with Asymmetric Shank Mass: Four videos are included that model damping in the right knee, which simulates a stroke gait. To compensate for the damping, four different PDW shank masses were tested. The intent was to examine if a damped (i.e., impaired, injured, damaged) knee is recognizable. If asymmetry with a damped knee is recognizable, is it possible to remove the perception of impairment by altering the impaired gait? We attempt to alter the damped gait by imposing a shank mass asymmetry. Four videos were recorded at 0%, 40%, 100%, and 118% shank mass asymmetry. The knee damping was chosen to be 0.275 Newton-radians, which was the highest knee damping value that allowed a stable gait pattern in the PDW.

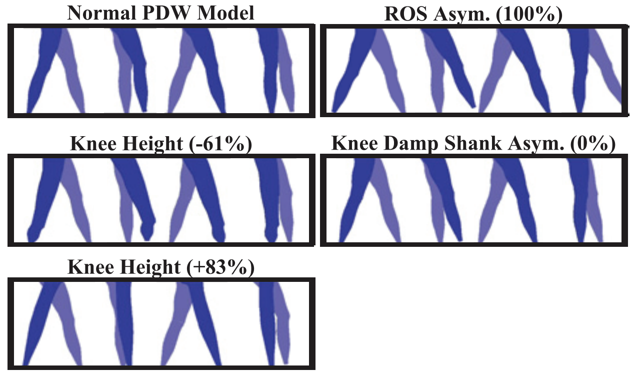

Fig. 3. Some of the passive dynamic walker models that were presented to participants. All videos are included in the supplemental material.

D. Statistical Evaluation

Participants rated walking videos on a symmetric 7-point Likert scale [25]. Because independent participants evaluate the walking videos and the ranked quantitative responses hold true throughout the Likert scale range, we assume a continuous linearity between Likert scale points and treat the acquired data as ordinal interval-level. A Chi-square goodness-of-fit test revealed that the comprehensive data does not follow a normal distribution (χ^2(6, N=23)=257, p <0.001). Data within each category was also found not to follow a normal distribution where the statistics of each video category Chi-squared will be described in the following results section. Because the data for each category of videos does not follow a normal distribution, we use a Kruskal-Wallis one-way analysis of variance non-parametric test to verify if the video ratings within each category of videos originated from the same distribution (i.e., are they statistically significantly the same). A Kruskal-Wallis one-way analysis of variance by ranks test (a.k.a. Kruskal-Wallis H test or Dunn's test) is a rank-based nonparametric multiple comparison test. This post-hoc test is used to determine if there are statistically significant differences between two or more videos in each video category rated on the 7-point Likert scale.

IV. RESULTS AND DISCUSSION

The perception of all 24 gaits in terms of the gait impairments was analyzed. The results of each category are shown in Figure 4. All videos in each category were compared to normal gait so that comparison statistics included both the normal and PDW modeled gait perception results for each category. Chi-squared goodness of fit analysis for each group revealed that the data within the group did not follow a normal distribution (p <0.001).

1) Gait Cadence: A statistically significant difference was found between the perceived impairment of different gait cadence (H(4, 466)=24.4, p <0.001). Post hoc analysis showed that participants were able to spot that there

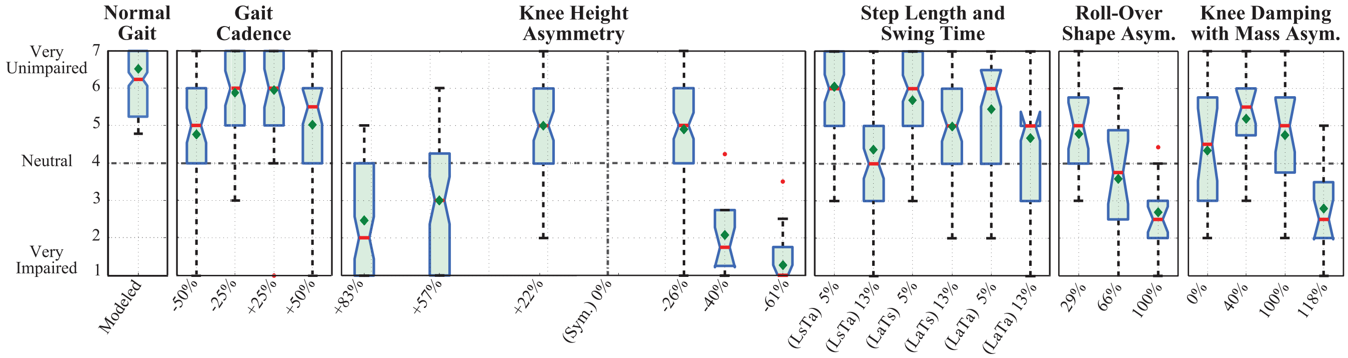

Fig. 4. Box and whiskers notch plots show participant's responses to gait videos.

was something abnormal and altered between the modeled normal walking pattern and a gait that is -50% and 50% faster. However, participants were not able to statistically significantly distinguish the normal gaits from gaits slowed down 25% and sped up 25% within this category. This may indicate that when seeing someone walking hastily or abnormally slow, it can be interpreted as out of the ordinary and draws attention. Although the impairment perception of this group was significantly different than normal walking, participants' medium rating was around 5: neutral to very unimpaired. Such a reaction may draw some attention, however would generally not be considered impaired.

2) Knee Height: A statistically significant difference was detected in knee height (H(6, 686)=327.6, $p < 0.001$). Participants perceived all presented knee location changes as statistically significantly different compared to the normal gait. Participants evaluated knee heights of $+83\%$, $+57\%$, -40%, and -61% as noticeably and highly abnormal or impaired, measuring their median, averages, and confidence intervals below neutral (4). Knee heights of $+22\%$ and -26% were only perceived as moderately impaired, which indicates that some knee height asymmetry with spatial and temporal gait symmetry could be dismissed as somewhat normal by observers. Participants were slightly more consistent in rating a low knee height as abnormal compared to higher knee locations (based on the confidence interval range). An inverse "U" pattern shows the increase of participants' gait impairment perception with knee height asymmetry, with a focal area between $+10\%$ and -20% knee height change. These results imply that given step length and step time symmetry, some knee height asymmetry can be unrecognizable or even perceived as unimpaired. As opposed to the other categories, alteration of knee height symmetry provoked the highest participant impairment ratings. It is shown that the higher the knee location is moved from its symmetric position, the more the gait is perceived as impaired. These results also suggest that a prosthetic design with a lowered knee location for functional improvement [9], [28] may be unnoticeable to some extent. It should be noted that the experiment did not examine if or how clothing would help to hide the effect of a prosthetic with a knee location in a different location, but these effects are likely to mask the knee location.

3) Spatial and Temporal Asymmetry: A statistically significant difference was found within this category group (H(6, 689)=146, p <0.001). Post-hoc analysis revealed that both step length (L) and swing time (T) left-right asymmetries produced statistically significant differences compared to normal gait when a 13% asymmetry was imposed, however at 5% asymmetry the gait was not perceived as impaired. That is, participants did not see small independent changes in swing time and step length as impaired. The gait was perceived as recognizably impaired at 13% step length asymmetry (LaTs) (mean rank = 238), while being perceived as more impaired at 13% swing time asymmetry (LsTa) (mean rank=193). However, the difference in impairment perception between these two videos was not statistically significantly different (Wilcoxon Z=0.55, p=0.58).

Separately, 5% LsTa and 5% LaTs did not produce a perception of impairment with participants, inherently suggesting that some gait asymmetry is not noticeable by observers and it should be noted that healthy individuals are known to have some asymmetric gait parameters [29]. However, it is interesting to note that 5% simultaneously in both measures produces a moderate perception of abnormality but with the confidence interval below the neutral perception rating. It may be concluded that compounding these asymmetries may cause greater perceptions in impairment, however this seems not to be the case for 13% LaTa. The 13% LaTa was rated similar to the 13% LaTs, while 13% LsTa was rated more impaired than 13% LaTa. A further study using more combinations of these asymmetric gait measures would help to understand the perceptual interactions with gait asymmetry more fully.

4) ROS Asymmetry: A statistically significant difference among ROS videos was found (H(3, 401)=68, p <0.001). Post hoc analysis showed participants perceived all ROS videos with a statistically significant difference compared to the normal gait. Walking videos with 29%, 66%, and 100% ROS asymmetry were perceived as minimally (mean rank=160), moderately (mean rank=127), and highly impaired (mean rank=102), respectively. Although more ROS asymmetries would clarify a trend, it can be concluded that with all factors symmetric, a ROS asymmetry below around 35% can pass as minimally impaired by observers. The trend implies that a ROS asymmetry below 15% may not be distinguishable from a normal and healthy gait. This is not surprising since ROS have large effects on gait dynamics and balance [7].

5) Knee Damping with Asymmetric Shank Mass: A statistically significant difference among videos in this category was found (H(4, 462)=89, $p < 0.001$). Participants perceived all but one (40%) shank asymmetry with knee damping videos in this category with a statistically significant difference compared to the normal gait. Although the 40% and 100% shank mass asymmetry had similar temporal asymmetries, 9.2% and 13%, respectively, only the 100% shank asymmetry was perceived as significantly different from normal gait. However, this may be caused by the spatial asymmetry in gait, which was 12% and 0% for the two videos respectively. Once the temporal asymmetry increased to 24% with a 4.5% spatial asymmetry, the perception of impairment was at its maximum. The results from this set of videos imply that if a person suffering from an impairment causing damping in a knee (injury, neurological, etc), that person could be seen as impaired or even slightly impaired. However, imposing an accompanying asymmetry, such as adding an asymmetric mass distribution, can potentially alleviate the perception of impairment. In other words, as one gait asymmetry is imposed that causes gait perception of impairment, a second gait asymmetry may be applied to some degree to negate these perceptions. This combination of asymmetries could lead to gait patterns that balance the perceptual and dynamic aspects of gait. This concealing of joint damping can potentially be achieved by altering other gait parameters such as having a foot roll-over shape or knee height asymmetry, however, this is still open for future studies.

V. Conclusions

This paper shows that there clearly is a gray and undefined area in human perception of gait impairment. Human gait may deviate from normal dynamics, but still be perceived as unimpaired. Orderly systematic deviation of gait included the change in gait cadence, knee height symmetry, step length and step time symmetry, roll-over-shape (ROS) symmetry, and knee damping symmetry. We showed that there is a range of knee joint height asymmetries where asymmetry may not be recognizable. Similarly, a certain range of asymmetry in step length or step time may not be recognizable by observers. Knee damping and mass asymmetry were independently varied to conclude that it is possible to alter the perception of a gait impairment by manipulating gait parameters such as adding additional mass to a leg and so changing the gait dynamics. Although twenty-four different walking patterns were analyzed, higher gait deviation types and resolutions need to be examined in order to explore the depths of the relationship between gait deviations and external perceptions.

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