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# Design and Pilot Study of a Gait Enhancing Mobile Shoe

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**Abstract**

Hemiparesis is a frequent and disabling consequence of stroke and can lead to asymmetric and inefficient walking patterns. Training on a split-belt treadmill, which has two separate treads driving each leg at a different speed, can correct such asymmetries post-stroke. However, the effects of split-belt treadmill training only partially transfer to everyday walking over ground and extended training sessions are required to achieve long-lasting effects. Our aim is to develop an alternative device, the Gait Enhancing Mobile Shoe (GEMS), that mimics the actions of the split-belt treadmill, but can be used during over-ground walking and in one's own home, thus enabling long-term training. The GEMS does not require any external power and is completely passive; all necessary forces are redirected from the natural forces present during walking. Three healthy subjects walked on the shoes for twenty minutes during which one GEMS generated a backward motion and the other GEMS generated a forward motion. Our preliminary experiments suggest that wearing the GEMS did cause subjects to modify coordination between the legs and these changes persisted when subjects returned to normal over-ground walking. The largest effects were observed in measures of temporal coordination (e.g., duration of double-support). These results suggest that the GEMS is capable of altering overground walking coordination in healthy controls and could potentially be used to correct gait asymmetries post-stroke.

**Keywords**

*locomotion · hemiparesis · rehabilitation · shoe · asymmetric gait · adaptation · learning*

## 1. Introduction

Stroke is a leading cause of long-term disability in the United States [18]. Many survivors suffer motor deficits that limit participation in activities of daily living, which may in turn contribute to poor aerobic fitness, diabetes, and metabolic syndrome [12]. One such deficit is 'hemiparetic' or asymmetric gait that results from unilateral lesions to leg motor areas. Hemiparetic gait is associated with decreased walking speed, reduced efficiency, and increased susceptibility to overuse injuries and falls, and thus reduces functional mobility [1, 3, 5, 6, 13, 33]. Therefore, treatments that could restore gait symmetry would have a significant impact on stroke rehabilitation.

Walking on a split-belt treadmill, which has two belts that can drive each leg at different speeds, changes the coordination between the legs (interlimb coordination) in adult humans [9, 16, 26, 36] and other animals [15, 19]. Following a period of split-belt walking, the treads are returned to the same speed ("tied-belts"), and the altered interlimb coordination is retained, demonstrating that individuals learned and stored a new walking pattern. It has been shown that split-belt training can improve abnormal coordination in individuals who have had a stroke [27, 32], suggesting that this may be useful as a rehabilitation device. However, these beneficial effects are only retained for a few minutes, and more permanent effects are only seen with training over several weeks [32]. Moreover, the improved coordination only transfers partially to everyday walking over ground [28]. These are both issues that could limit the therapeutic potential of the split-belt treadmill in rehabilitation.

Our goal is to develop a novel device that can alter interlimb coordination while walking over ground, but would lead to longer-lasting improvements to walking in normal environments compared to a split-belt treadmill. To address the first issue of retention, we focused on a design that would be affordable, portable, and passive, thus enabling at-home use and allowing for longer training periods than what is currently available with the split-belt treadmill. To address the second issue of over-ground transfer, our hypothesis is that transfer would be improved if training occurred over ground, as opposed to on a treadmill. This is based on a number of studies showing that learning is best expressed when the training environment matches the testing environment [2, 32, 35]. Therefore, we also focused our designs on those that could perturb over-ground gait, anticipating that this would lead to larger changes in normal over-ground walking patterns.

This concept of a mobile shoe that can disrupt over-ground walking coordination has been developed into the Gait Enhancing Mobile Shoe (GEMS), shown in Figure 1. The GEMS presented in this paper is the successor of two previous versions [10, 11]. All versions have been shoes with wheels that have caused the foot to move relative to the ground during stance phase, thus changing coordination parameters such as step-length. The first version [10] was passive and had no control of the backward sliding motion of the foot during stance – this resulted in a jerky and unpredictable perturbation comparable

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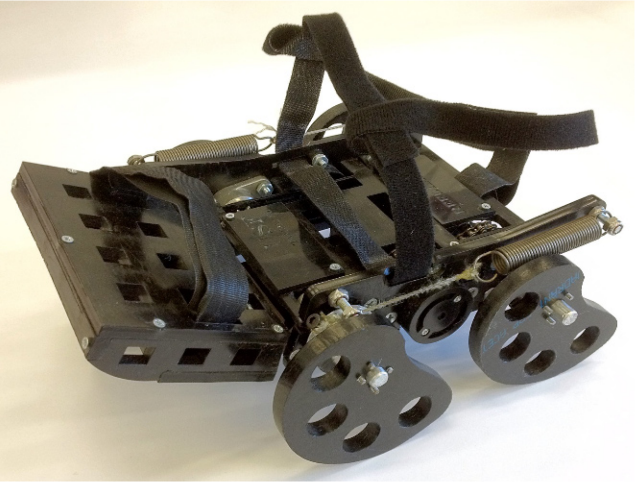

*Figure 1. The Gait Enhancing Mobile Shoe is designed to generate a motion relative to ground. The shoe pictured here generates a forward motion during the stance phase. A similar shoe with the wheels facing the opposite direction can generate a backward motion.*

to slipping on a slippery surface, like ice. The second version [11] eliminated the problem of jerkiness and provided a smooth and controlled horizontal motion, however the various motion controls caused this device to be too high off the ground and too heavy for actual subject testing.

The GEMS version outlined in this paper uses an Archimedean spiral wheel shape to generate motion relative to ground and unidirectional dampers to regulate the shoe velocity. This shoe does not require any power source to operate and can be worn for extended periods of time in different environments including one's own home. In addition, this version uses one shoe on each foot where one generates a forward motion and the other generates a backward motion; the opposite action of the two shoes causes a larger change in interlimb coordination than what was possible with the previous versions of the GEMS.

This paper will discuss the background of normal gait and gait rehabilitation in Section 2, the design of both the forward and backward moving GEMS in Section 3, and preliminary experiments using two shoes moving in opposite directions in Section 4.

## 2. Background

### 2.1. Gait Phases and Reaction Forces

Since this paper presents a gait correction method based on the Gait Enhancing Mobile Shoe (GEMS), it is important to compare the motion of a normal human gait pattern to the motion generated by the shoe. The gait cycle can be divided into two distinct phases: the stance phase and the swing phase [24]. Figure 2 shows the stance phase, during which one foot is in contact with the ground, as shown in both a typical gait (top) and while wearing the backward moving GEMS (bottom). The wheels on the shoe can be turned to face the opposite direction, which will have the effect of generating a forward motion. The forward and backward moving GEMS can then be worn on opposite feet to generate a large differential motion during their respective stance phases.

The graph in Figure 3 depicts the horizontal and vertical forces applied by the foot during adult walking starting at heel contact. During the stance phase, a slightly variable vertical force is applied while the horizontal force switches from forward to backward. It is noted that the horizontal reaction force switches at 33% of the gait cycle from accelerating the body backward to accelerating the body forward. To generate the necessary horizontal force, the GEMS passively converts the vertical force from the wearer during the stance phase and redirects it into a horizontal motion. The ideal motion that the foot should travel is not currently known, but, to avoid triggering the balancing reflexes, the motion of the shoe should be consistent and smooth. Treadmills have a fairly constant velocity, whereas the backward moving GEMS starts and ends slow with a peak velocity in the middle. At heel contact, the wheels of the GEMS start pushing the wearer's foot backward similar to the motion experienced when stepping on a moving treadmill. While in the stance phase, the GEMS converts the body weight to a controlled horizontal backward motion.

### 2.2. Correcting Gait

Practicing walking on a split-belt treadmill can correct abnormal walking coordination in individuals with hemiparesis due to stroke or central nervous system damage [16, 17, 22, 26, 27]. Asymmetric gait can manifest as a spatial asymmetry, in which steps taken on one side are longer than those on the other. It can also manifest as a temporal asymmetry, where the timing is uneven on the paretic and non-paretic sides. Temporal asymmetries are often measured as differences in the duration of double support periods, which are the amount of time both feet are simultaneously contacting the ground and are measured separately for the paretic and non-paretic sides. The GEMS was designed to cause changes in both spatial and temporal gait symmetry.

The forward-GEMS and the backward-GEMS were expected to generate opposite effects that work together when worn on opposite feet. We predicted that the backward-GEMS would cause the steps on the side with the GEMS to be larger, since individuals would compensate for the backward rolling motion by placing their foot farther forward in stance, thus increasing the distance between the two feet. Similarly, since the stride would be longer, the backward-GEMS may also lengthen the duration of stance relative to the other side. With extended stance duration, the amount of time spent in double-support at the end of stance would likely increase as well. The forward-GEMS would have the opposite effect, shortening steps and double-support durations.

Although the original idea of the GEMS is derived from the motion of the split-belt-treadmill, there are distinct differences between walking on the GEMS and walking on a split-belt treadmill with asymmetric belt velocities. While the body's velocity relative to ground is zero on a split-belt treadmill, the relative velocity of the GEMS is non-zero and forward. The GEMS forces the wearer's foot forward or backward whereas the treadmill moves both feet backward, but at different speeds. For both the split-belt treadmill and the GEMS, the relative velocity between both feet is similar, and the forward-moving GEMS takes the place of the slower tread. To further compare the differences of these environments, future research includes using an asymmetric passive dynamic walker to study the differences of walking on the GEMS, a split-belt treadmill, and walking over ground [14].

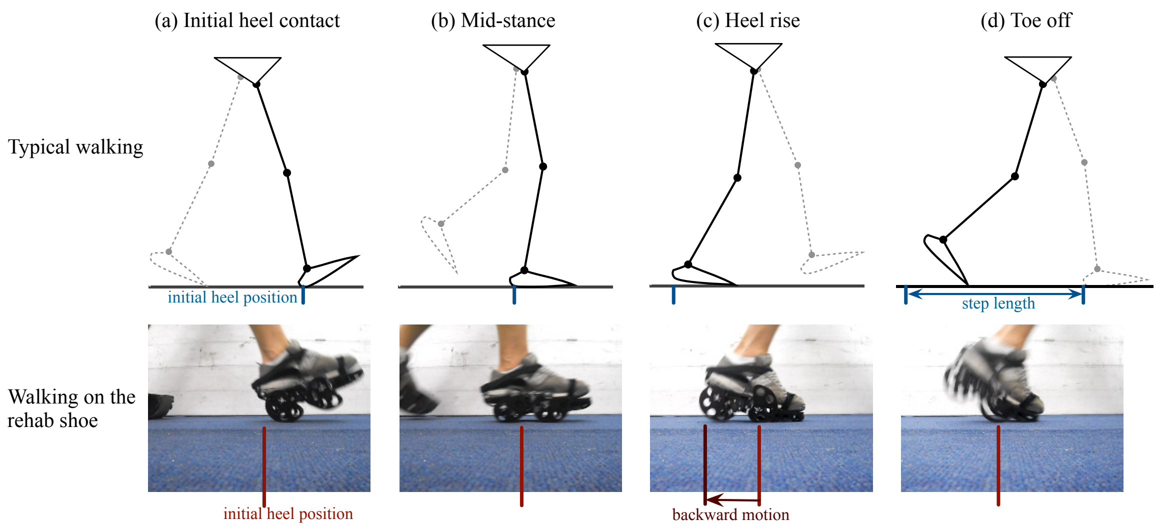


*Figure 2.* *The four phases of walking relevant to the Gait Enhancing Mobile Shoe design are shown above for a typical walking pattern (top) and when walking on the backward moving GEMS (bottom). Although not shown here, the shoe can be constructed to generate a forward motion.*

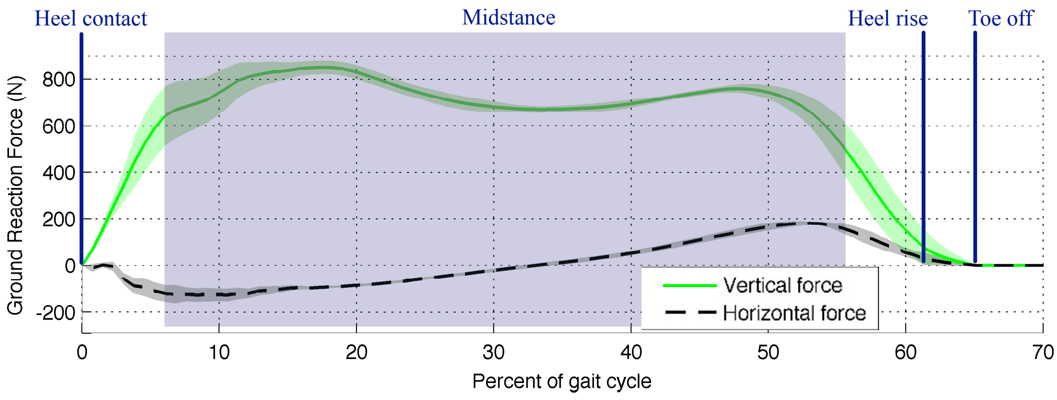


*Figure 3.* *The horizontal (fore-aft) and vertical forces change throughout the gait cycle. Our GEMS uses these changing forces to generate the necessary motions for altering gait patterns. The shaded regions represent the standard deviation of seven steps.*

Based on our hypothesis, prolonged use of the GEMS should change interlimb coordination in individuals with asymmetric gait and allow individuals to develop a more persistent symmetric gait. Training an individual with the GEMS may also strengthen muscles due to the different walking pattern that is developed [25], which in turn could alter the individual's gait. Future studies could include EMGs to more clearly determine the change in muscle activation patterns.

## 2.3. GEMS and Context Dependent Learning

It is well-known that learning is best expressed when testing and training environments, or "contexts", match [2, 32, 35]. During split-belt walking, individuals are trained on a treadmill and effects are tested during over-ground walking. In this situation, there are several differences between the training and testing environments, such as visual flow and vestibular information signaling forward movement, that likely limit the expression of learning in the over-ground context. Visual cues appear to be particularly important for context awareness [8]. For example, vision of an upcoming escalator causes individuals to make feed-forward (i.e., predictive) changes in posture to accommodate the moving escalator – namely, they lean forward as they step on. These visual cues, coupled with prior experience, are so powerful that predictive postural responses persist even when the escalator is obviously not moving [7, 30]. A recent study of split-belt walking showed that transfer to over-ground walking is enhanced when subjects are blindfolded during training on the treadmill and testing over ground [34]. Since blindfolding eliminates visual cues about the environment, this also suggests that vision is a key factor in determining the context-dependence of learning. Since it is not realistic to blindfold stroke patients during gait training, we designed the GEMS so that training could occur during over-ground walking, thus visual cues during training and testing would be conserved.

# 3. GEMS Design

## 3.1. First GEMS Design

The first version of the GEMS [10] was simple and successful at pushing the wearer's foot backward relative to the opposite foot, making the step length larger on one side than the other. However, due to this version's lack of control and damping, the backward motion was very jerky and variable, and it was difficult for people to learn a new pattern to efficiently walk on such an unpredictable device. Although this version showed a brief change in interlimb coordination when the shoe was removed, it is hypothesized that the uncontrolled and variable motion of this version triggered the body's balancing reflexes, which in turn prohibited any long-term change to their gait pattern. While it was a simple and durable design that endured over 5000 steps without maintenance, this version also had low adjustability in backward motion, velocity, and travel distance.

## 3.2. Second GEMS Design

In contrast to the first version, which lacked adjustability and control of motion, the second version [11] also generated the backward motion passively, but used a magnetic particle brake and a microcontroller circuit. Instead of using traditional wheels, it utilized Archimedean spiral shaped wheels, which converted the downward forces from the wearer into a horizontal motion. The brake controlled the damping in the shoe according to the gait cycle phase. Although the second version produced a smooth transition and a consistent foot velocity, it was too heavy, too tall, and somewhat unreliable for extensive human testing.

## 3.3. Third Time's a Charm

The third GEMS, which is reported here, is a balance between the first version, which was too simple and unpredictable, and the second version, which was complicated and unreliable. The third version is "just right" in that it is low to the ground, completely passive, and provides sufficient damping for a consistent shoe motion. The weight is adequate at 1.5 kg, but would ideally be reduced. The overall dimensions of the GEMS are 28 cm long, 20 cm wide, and 5 cm high. The wearer stands 8.3 cm above ground at initial heel contact and 3.8 cm above the ground at the end of stance phase. This version is also reliable enough to allow for at least one hour of continuous training. Additionally, this design was adapted so the shoe could either push the wearer's foot backward or forward. This design flexibility makes it possible to use two shoes simultaneously, allowing one foot to be moved backward and the other to be moved forward during the respective stance phases in order to increase the applied perturbation.

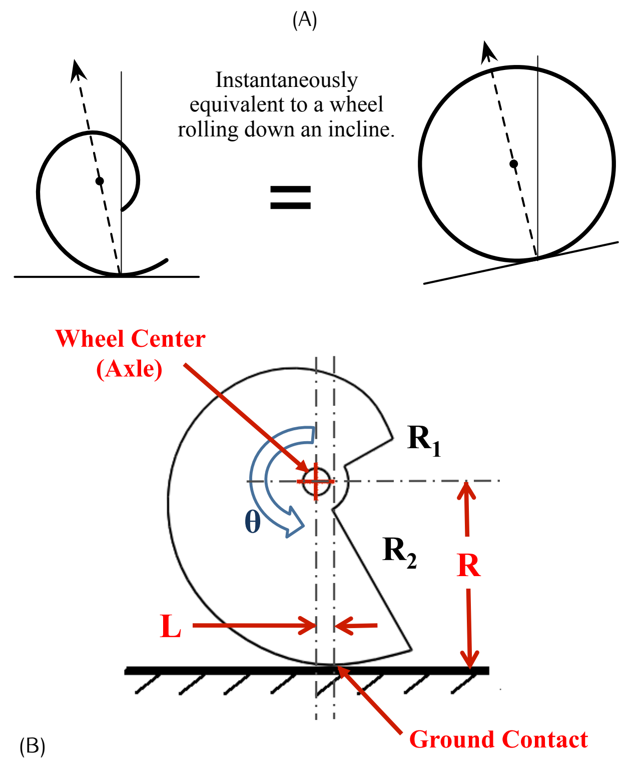


*Figure 4.* *GEMS wheel shape* **(A)** *The shape of the wheel is defined as an Archimedean spiral. This shape redirects the downward force to generate a forward or backward motion.* **(B)** *Parameters: $R$ is the instantaneous radius and $L$ is the distance from ground contact to wheel center.*

## 3.4. GEMS Wheel Shape

An essential aspect of the GEMS design is the shape of the wheels. The wheel shape is designed around the concept of the Archimedean spiral shown in Figure 4.A and is similar to the wheel used in the second GEMS version [11]. When attached to an axle, this type of wheel shape redirects the wearer's weight during the stance phase into a horizontal backward or forward motion depending on the direction of the wheel slope. This wheel shape closely mimics a circular wheel rolling down a hill, however, the slope is attached to the foot. The size of the wheel shape and the horizontal reaction force is determined by (1) and (2), respectively, as

$$R(\theta) = b\theta^{\frac{1}{n}} \tag{1}$$

and

$$F_{H,avg} = \frac{1}{R_2 - R_1} \int_{R_1}^{R_2} F_H(R)dr \tag{2}$$

where

$$F_H = \frac{F_V * L}{R} \,. \tag{3}$$

The parameters of the GEMS wheels are define in Figure 4.B, $F_V$ is the vertical force from the wearer, and $F_H$ is the horizontal generated force. For the preliminary tests reported here, we have designed the wheels to change linearly with the radius. However, changing the slope at different points will allow for an optimization of the force generated during each instant during the stance phase. The optimization of the wheel shape, along with determining the ideal trajectory of the foot, is left for future work.

The wheel parameters for this experiment were chosen such that the largest radius was 7.0 cm, the shortest radius was 2.5 cm, and $n$ is 1 so that the wheels would generate an average horizontal backward force of 160 N given an 800 N vertical downward force from the wearer. Since the backward force is based on the weight of the wearer, the force will scale proportionally with the weight of the person. The generated horizontal force can also be adjusted further to fit a range of individuals by changing the shape and size of the GEMS wheels. A larger difference between $R_1$ and $R_2$ and a larger value for $n$ will yield a larger horizontal force.

## 3.5. Shoe Frame Structure

The shoe is completely manufactured out of delrin plastic, which was cut using a laser cutter. Using delrin plastic for the frame allowed for a light and strong frame and a more rapid manufacturing process. The frame consists of a front half and a back half connected by a hinge, which is placed near the ball of the wearer's foot and is able to angle up to thirty degrees upward. Unlike previous GEMS, this version has a more natural feel to it by letting it deform as the user toes off and the two hinged parts angle toward each other. When the wheels have rotated fully, the bottom of the wearer's shoe sits 3.8 cm off the ground.

## 3.6. Control of Ground Reaction Forces

Each GEMS uses one unidirectional damper that prevents a swift and jerky backward progression once the user steps on the shoe. The damper has an over-running clutch (or a free-wheel clutch) that exerts a damping force in only one direction of wheel rotation, but does not damp the mechanism when the shoe is resetting back to its initial state in preparation for another step. An over-running clutch acts similar to a continuous ratchet mechanism; it allows rotation in one direction and limits rotation in the opposite direction. Based on the torque exerted by the wheels, the damper was sized to 1.9 N-m, which provides sufficient damping to decrease the velocity of the motion to a comfortable and natural velocity magnitude. The damping torque works for wearers with a weight in the range of 68 kg to 86 kg and can be adjusted as needed for other wearers. In order to keep the GEMS velocity steady for users out of this weight range, the damper must be replaced by a weaker damper for lighter wearers or a stronger one for heavier wearers. Whereas the generated horizontal force scales with the wearer's weight, the damper force is independent of the weight.

The damper is coupled to the axle of the GEMS with a chain and two sprockets, one on the axle and one on the damper, as illustrated in Figure 5. As the wearer steps onto the shoe, the wheels apply a torque onto both axels, one of which is coupled to the damper. Once the shoe reaches the limit of its motion at toe off and the foot is lifted off the ground, the spring mechanism resets the wheels to their original positions to prepare for the next step starting at heel contact. The spring reset mechanism works by extending a spring, which is located on the side of the shoe, as the wheels of the GEMS rotate. As the wearer toes off into the swing phase, the spring pulls the wheels back to their initial positions.

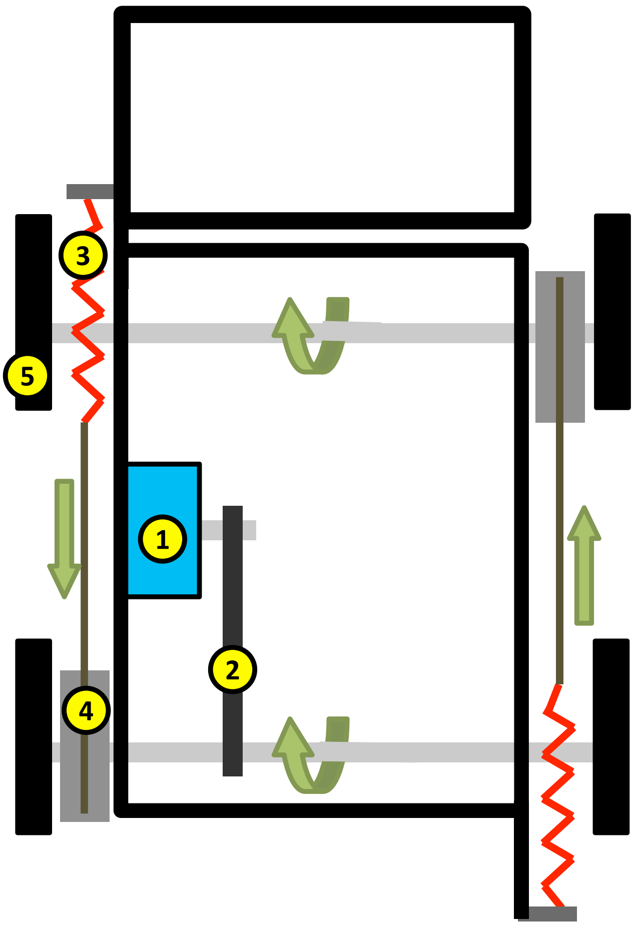


*Figure 5. Forward moving GEMS top view schematic of Unidirectional Damper and Reset Mechanism. (1) Unidirectional Damper, (2) Steel Chain, (3) Reset Spring, (4) Reset Pulley, and (5) GEMS Wheel.*

## 3.7. Second Direction Shoe

The design of this shoe is flexible in that the shoe can redirect the downward forces to either a forward or backward motion by turning the wheels around so the slope goes in the opposite direction. This is beneficial since a configuration in which one foot moves forward and one foot moves backward during the respective stance phases would generate the greatest motion differential between both feet. One GEMS was measured to move the foot back an average of 17.8 cm during each stance phase. Adding a forward-GEMS to the other foot should create twice the differential between the feet during waking.

In the backward moving shoe, the unidirectional damper is coupled with the front axle, leaving the back axle undamped. This was done because the user is pushing forward at initial heel contact, so full force is needed to generate the backward motion. As the wearer transitions to the middle and end of the stance phase, the damper applies a torque to slow the motion that arises from the person pushing backward.

The forward moving shoe is opposite; the unidirectional damper is coupled with the rear axle, leaving the front axle undamped. The forces applied to the forward shoe are initially in the direction of the desired motion; at initial heel contact, the shoe generates a forward motion and the user is pushing forward, thus the damper is engaged to slow the large motion. As the user transitions to the middle and end of the stance phase, the forces are pushing backward, but the shoe will continue to generate a forward motion since the forces from the wheel are strong enough to overcome the horizontal pushing force and the damper will no longer be affecting the motion.

The forces involved are currently linear and are based on the simple shape of the wheel. The interaction of these forces can be optimized to generate a large range of different force profiles that could be used in several different ways. One alternative application is to use two shoes that propel a person forward during both steps to increase their natural walking speed. Does the increase in forward progression make up for the extra weight and slight increase in the height of the shoe? The answer is unclear at the moment. Another use of these shoes is to test walking perturbations where the force in the shoe could be customized or remotely actuated to generate a sudden force to measure how people recover from unexpected foot motions.

## 4. Preliminary Walking Study

### 4.1. Subjects

Three healthy females (aged $22.4 \pm 0.08$ years), free from neurological or musculoskeletal impairment, participated in this study. All participants gave informed written consent prior to participating and the experimental protocols were approved by the Einstein Healthcare Network Institutional Review Board.

### 4.2. Experimental Setup

Kinematic data were collected using the CODAmotion active marker system (Charmwood Dynamics, Leicestershire, UK) at $100$ Hz. Infrared-emitting markers were placed bilaterally over the toe (fifth metatarsal head), ankle (lateral malleolus), knee (intra-joint space), hip (greater trochanter), pelvis (iliac crest), and shoulder (acromion process). Walking was recorded while subjects walked along a $6.5$ m path over ground. Each experiment began with $10$ baseline trials (one trial = one pass on walking path = approximately $8$-$12$ strides), in which participants were instructed to walk at a comfortable pace in their own athletic sneakers (Figure 6).

Immediately following the baseline trials, the two GEMS were strapped on the participant's feet with the forward-rolling GEMS attached to the subject's dominant foot (the right foot, for these three subjects), and the backward-rolling GEMS attached to the non-dominant foot. Once the two GEMS were secured, $10$ trials were recorded ("Early Adaptation"). Then subjects proceeded to walk for an additional $10$ min while wearing the two GEMS in order to adapt. During this $10$ min, subjects continued walking at their preferred speed, as established during the Early Adaptation period, along the same path used in the recorded trials. The number of steps during adaptation ranged from $252$ to $366$ (group mean $309.3 \pm 56.5$ steps). At the end of this period, an additional $10$ trials while wearing the GEMS were recorded ("Late


*Figure 6. Experimental paradigm. Solid lines show periods that were recorded. The dashed line (adaptation) was not recorded. Subjects wore the GEMS during the red periods, and walked in normal sneakers for the black periods (Baseline and Post-Adaptation). All of the recorded periods consisted of ten trials. A trial was equivalent to $1$ pass across the over ground walking path, which took $8$-$12$ steps. The unrecorded adaptation period (dashed line) lasted $10$ min, which was equivalent to $309.3 \pm 56.5$ steps (mean $\pm$ SD).*

Adaptation"). The subjects were then instructed to sit down to remove the GEMS, and then complete $10$ additional walking trials wearing their own athletic sneakers ("Post-Adaptation"). This Post-Adaptation period allowed us to assess if the GEMS caused subjects to learn a new walking pattern.

### 4.3. Data Analysis

To assess walking symmetry during Baseline, Early Adaptation, Late Adaptation, and Post-Adaptation periods, we examined two different measures: step length difference and double-support difference. Step length was calculated as the antero-posterior distance between malleolus markers of each limb at heel strike, and was defined as "right" or "left" depending on which leg is leading (Figure 7.A). Note that step length is calculated at the instant of heel contact. We calculated a difference in step lengths (left-right) in order to assess whether steps were the same size (i.e., symmetric gait) or whether they were different (i.e., asymmetric gait). A second measure to quantify walking symmetry was based on the difference in the duration of double support periods during gait (Figure 7.B). Double support was calculated as a percentage of time during the stride cycle that two feet were on the ground at the same time – right double support occurred at the end of right side stance phase and likewise for left double support. Difference in double support was equal to the percent double support on the right side subtracted from that on the left. A difference close to zero would indicate near-symmetric gait. Note that the weight of the GEMS shoes is different than the weight of the baseline testing with sneakers, but the weight is changed equally on both feet. The change in weight is likely to have a slight symmetric effect on the step lengths, but the measures used here are all based on the differences between the legs, which will not be significantly affected by the testing procedures.

### 4.4. Results

Figures 7.C and 7.D show step length difference and double support difference, respectively, from each of the three subjects for the Baseline, Early Adaptation, Late Adaptation, and Post-Adaptation periods. Averages within subjects were calculated for the entire Baseline period (approximately $30$ steps), the first five steps of Early Adaptation, and the entire Late Adaptation and Post-Adaptation periods. Wearing the GEMS did not appear to change the step length difference in a consistent manner across subjects (compare Early and Late Adaptation to Baseline in Figure 7.C). Our preliminary results showed that the difference between Post-Adaptation, when subjects returned to walking in normal shoes, and Baseline was

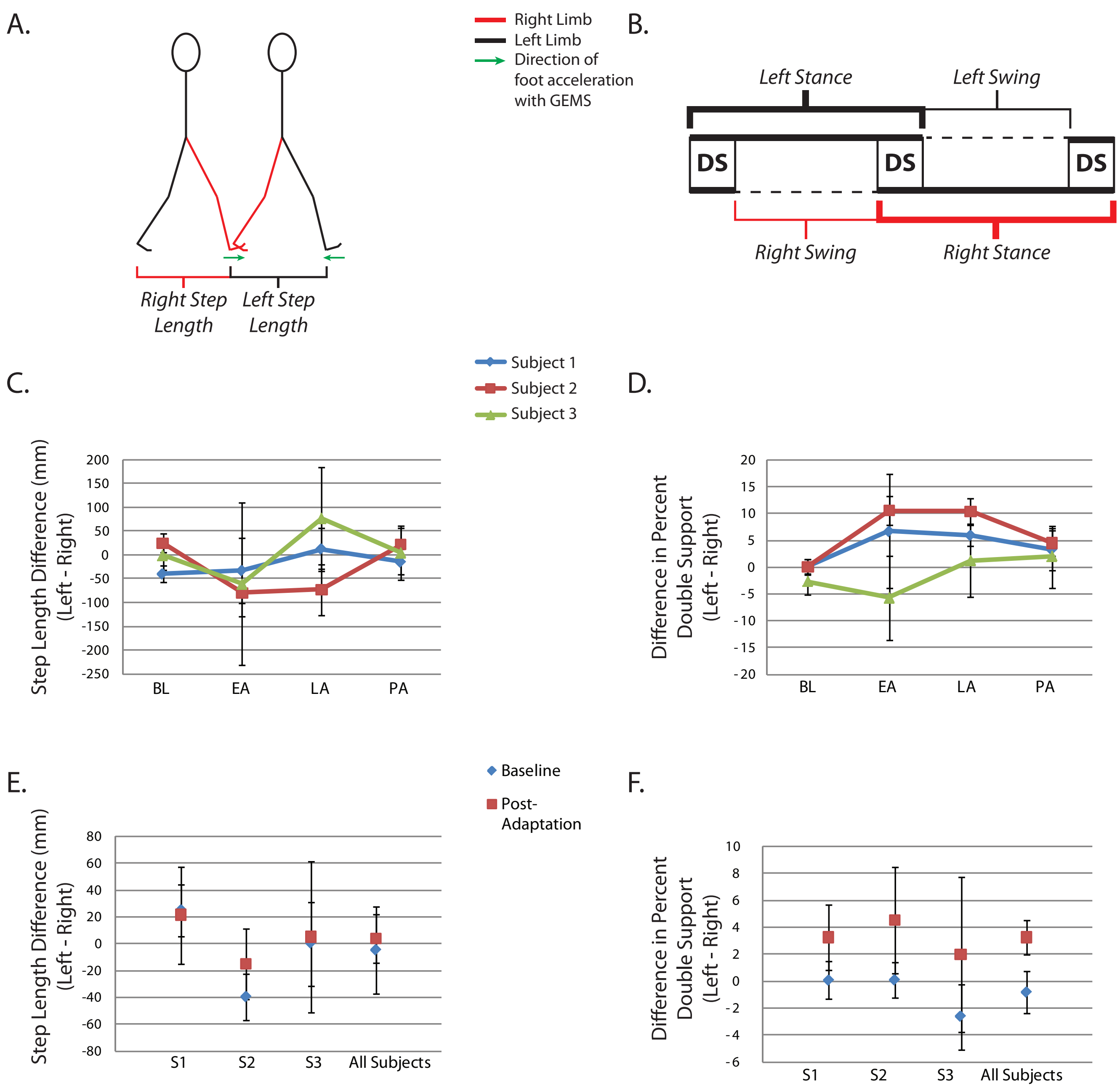


*Figure 7.* **(A)** *Step length is defined as the distance between malleolus (ankle) markers at the instant of heel strike, as shown in the stick figure, and was defined as right (red) or left (black) depending on which leg was leading. Note that the forward-rolling GEMS was on the right foot, and the backward-rolling GEMS on the left.* **(B)** *Double support duration during stride cycle. Stance and swing phases are represented by solid and dashed lines, respectively (red = right; black = left). Double support occurs when both feet are contacting the ground (shown by shaded boxes), and is termed "right" or "left" by the limb stance which it follows.* **(C)** *Single-subject data showing the average difference in step length (right-left; ± standard deviation), during baseline (BL), early adaptation (EA), late adaptation (LA), and post-adaptation (PA).* **(D)** *Single-subject differences in double support duration, as shown in C. Double support difference was calculated by subtracting the duration of right double support (expressed as a percent of stride cycle) from the duration of left double support.* **(E)** *Summary of single-subject and group-averaged differences in step length between baseline (blue diamonds) and post-adaptation (red squares). Error bars show* 1 *standard deviation* **(F)** *Summary of single-subject and group-averaged differences in double support time between baseline and post-adaptation, as shown in E.*

$8.85 \pm 14.35$ mm (Figure 7.E). We used these results to perform a power analysis to estimate the number of subjects required to show a significant effect (based on paired t-tests between baseline and Post-Adaptation). We calculated a moderate effect size of $0.68$. With power set to $0.8$, we estimated our sample size to be $18$ subjects, which is similar to those tested in previous studies of split-belt adaptation. If the trend we see in our preliminary results continues, this would indicate that the GEMS was capable of modifying step length symmetry in control subjects.

We found that the effect of wearing the GEMS on double-support difference was greater than the effect on step length difference. In particular, subjects 1 and 2 showed altered double support durations between Baseline and Early Adaptation in the positive direction, indicating that the GEMS caused the left (backward-GEMS) double-support phase to be longer than that on the right (forward-GEMS). Note that this is what we had predicted, as discussed in Section 2.2. While double-support difference in subject 3 changed in the negative direction during Early Adaptation, by Late Adaptation the change was positive and similar to the trend in the other subjects. The mean change between Baseline and Post-Adaptation for all subjects was $4.08 \pm 0.78$ (units = % total stride time), shown in Figures 7.D and 7.F, which indicates that they learned a new double-support relationship between the legs while walking with the GEMS. This effect size was very large ($5.23$) leading to an estimated sample size of $3$ (power = $0.8$). Since double support is a measure of temporal interlimb coordination (i.e., determined by "when" the limb is placed during gait), our preliminary data suggest that the GEMS shows promise in changing temporal relationships between the legs. We plan to continue collecting data on $18$ subjects to determine if this result is sustained with a larger sample size. If so, this would indicate that practicing walking with the GEMS can induce large changes in double-support symmetry and may be effective in correcting temporal gait asymmetries post-stroke.

## 5. Conclusions

We have successfully developed a Gait Enhancing Mobile Shoe (GEMS), which is able to generate a smooth and consistent backward and/or forward motion. The GEMS outlined in this paper is the successor of previous models and builds upon previous design concepts. This current design of the GEMS resulted in a lighter, smoother shoe that was lower to the ground. While the shoe provides similar motions to a split-belt treadmill in a completely passive way, it exhibits various benefits, which include gait training in different environments and locations, and gait training over a longer period of time. These benefits will allow for further investigation of the long-term after-effects of extended training sessions, which we hypothesize will lead to prolonged retention of the corrected gait in individuals with asymmetric gaits.

Here, we conducted initial experiments to examine the strategies used by human subjects to alter their walking patterns while wearing the GEMS, which was designed to perturb interlimb coordination using either one or two shoes. We found that the GEMS was able to perturb temporal (double support duration), but not spatial coordination (step length). Adaptation to the perturbation in temporal coordination was characterized by a lengthening of the double support phase on the left side (wearing the backward GEMS) as compared to the right side (wearing the forward GEMS). This asymmetry in double support continued even when the GEMS were removed and subjects resumed walking with normal shoes (Figure 7.F). This indicates that a new coordination was learned and stored following a period of walking with the GEMS.

Adaptation reflects a re-calibration of motor commands in response to changes in the environment (e.g., icy surfaces) or in oneself (e.g., injury) [21, 26, 31]. It is a form of short-term learning that occurs on a time scale of minutes to hours and is likely a precursor to more permanent forms of motor learning [29]. Recently, it has been suggested that adaptation training on a split-belt treadmill, which also perturbs interlimb coordination, may help to improve abnormal gait coordination in individuals who have had a stroke [26, 28, 29]. However, these effects were short-lived unless training occurred over the course of weeks [29], and the improved coordination did not transfer completely to normal walking over ground [28]. These issues may limit the feasibility of using the split-belt treadmill as a rehabilitation device.

We designed the GEMS as an alternative device that would perturb gait, but would circumvent the limitations of the split-belt treadmill. Our design is portable, low-cost, and passive, allowing it to be used at home or in smaller clinical settings, thus enabling training over longer periods than what is currently available. We also designed the GEMS so that it could be worn during over-ground walking, thus maximizing improvement in real-world gait. Indeed, our preliminary data shows that control subjects were able to adapt temporal coordination to the GEMS and these changes in coordination persisted even when tested during normal walking over ground. Note that we do not know why spatial coordination was unaffected by the GEMS, although it has been suggested that these two aspects of gait are controlled by separate neural substrates [4, 20, 37]. This could be investigated in future studies. Nonetheless, our results suggest that the GEMS could be an effective rehabilitation tool to improve over-ground temporal gait symmetry post-stroke. We feel that this would be important for rehabilitation since temporal asymmetries commonly result from hemiparesis post-stroke [5, 33] and are correlated with reduced gait speed [23], which is a marker of impaired functional walking ability. Investigating whether GEMS training improves abnormal coordination and functional mobility post-stroke is one of our future goals.

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