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Combined Gait Asymmetry Metric

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Abstract— **People with physical impairments often have asymmetric gait. To evaluate if their overall symmetry is improving during intervention, there needs to be a simple metric that can help classify gait patterns that includes multiple measures of gait asymmetry. The Combined Gait Asymmetry Metric presented here is based on the Mahalanobis distance of multiple step parameters. We tested able-bodied subjects with perturbations that involve a change in leg length, the addition of ankle weights, and a combination of both perturbations. The Mahalanobis distances are calculated from perfect symmetry to all points in the data to analyze the effects of the different perturbations. The metric demonstrates how an overall view of symmetry can give a better perspective of asymmetry than only looking at a few individual parameters. This metric is straightforward and can be extended to include large numbers of spatiotemporal, kinematic, and kinetic parameters that more completely evaluate a change in gait symmetry.**

I. Introduction

This paper introduces the Combined Gait Asymmetry Metric that can use spatiotemporal, kinematic, and kinetic gait parameters, to classify overall symmetry. To assess this metric, the study used measures of spatio/temporal and kinetic data that were collected from ten subjects who were all put through a series of ten asymmetric alterations including: a change in leg length, the addition of masses at the ankles, and a combination of both perturbations. The gait patterns were processed to five gait parameters: step length, step time, vertical ground reaction force, push off force, and braking force. These measures were then put together and the Mahalanobis distances were found from the origin (i.e., ideal symmetry). The combined measure of symmetry that was obtained using this metric showed similar trend to an earlier analysis, performed by examining the individual parameters [1]. In addition, this metric is versatile enough and could include any spatio/temporal, kinematic, and kinetic gait parameters, and it can be used to look for patterns in subsets of the gait parameters. This paper presents an initial assessment of the metric using five gait parameters.

II. Background

Asymmetry is inherent in human gait, and all able bodied people have some gait parameters (e.g., spatiotemporal, kinematic, or kinetic) that can be up to 6% asymmetric [2], [3], [4]. Asymmetry of a person's gait is typically amplified by physical impairments such as neuro-degenerative diseases, amputation, and leg length inequality [3], [5], [6]. This asymmetry in gait is a result of changes to a person's neuromuscular systems that govern their lower limbs during gait.

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Several rehabilitation techniques and devices are currently used to correct and aid patients with these impairments. However, the focus of these rehabilitation methodologies is to restore symmetry in spatiotemporal, kinematic, and/or kinetic parameters between the lower limbs [7], [8].

The study presented here formulates a simple metric to measure and classify the effects of asymmetric alterations that were applied to a combination of changes in leg length and the addition of masses at the ankle [9], [6]. Several symmetry indexes [10], [7] have been used to quantify the magnitude of gait asymmetry. The purpose of all gait metrics is to provide an objective evaluation of a subject's gait by analyzing data that helps clinicians to verify their subjective evaluation. Although past symmetry indexes serve as good measures of symmetry, they are not always adequate in classifying the effects of a large range of altered gait patterns. Several metrics have been implemented in order to classify differences in walking based on gait parameters. One is the normalcy index, also known as the Gillette Gait Index (GGI), which looked at a distance measure between gait parameters of healthy subject's gait and subjects with cerebral palsy [11], [12]. The study was able to assign ranges using distance values that correspond to the severity of the patient's condition, but does not generalize the walking patterns of other conditions.

Some previous analyses were limited to either kinematics, like GGI and gait deviation index (GDI) for kinematics [11], [13], [14] or kinetics, like GDI for kinetics [15], [16]. Other metrics have had success combining kinetics and kinematics, like the extended GGI and comprehensive asymmetry index (CAI) [17], [18]. The CAI is similar to the metric presented in this paper in that it looks at gait asymmetry and presents a distance metric/index to classify the gait. However, the CAI may not be complete as it uses simple differences of the parameters and euclidean distances to construct the index.

To build an exhaustive gait metric that looks at asymmetry, it must include gait parameters of spatiotemporal, kinematic, and kinetic measures [12]. Using a symmetry index is beneficial since it eliminates the need to scale values of different kinds of parameters. In case of the CAI, the difference between the left and right parameters is used, but the problem with that measure is that the asymmetry of each parameter is not normalized. Additionally, the CAI uses principle component analysis (PCA) to reduce the dimensionality of the data to increase sensitivity to small changes. PCA was used in the GGI [11] as well, and it focused on uncorrelating the highly correlated kinematic parameters. Following PCA, both CAI and GGI use euclidean distance to define their metric/index. Euclidean distance is used in the GDI [14] as well where singular variable decomposition (SVD) is used instead of PCA. Euclidean distances are simple to use for the metrics, however, it may not be the best measure with high dimensional data with different magnitudes.

In this study, the Mahalanobis distance [19] is used to generate the metric based on the individual gait parameters. The Mahalanobis distance has been used to develop prior gait metrics such as the classification of subjects using ground reaction forces, extended index, and to differentiate gait patterns between normal and gait affected by stroke [20], [17], [21]. Mahalanobis distance is designed for high dimensional data because the covariance of the data is taken into consideration. In the case of euclidean distance, the covariance is an identity matrix so all gait parameters are given an equal weighting. The inclusion of the covariance into the Mahalanobis equation makes it better for scaling of distance measures in multi-dimensional space. Some studies also used a combination of PCA and Mahalanobis distance to identify abnormal gait, classify knee kinematics and kinetics for normal and irregular gait patterns [22], and quantify the effects of anterior cruciate ligament reconstruction [23]. Our study looks at another method of using the Mahalanobis distance to quantify gait patterns using a combination of individual gait measures.

III. Experimental Design

The experimental study was conducted on able-bodied subjects, with unaltered gait, and no prior physical impairments. The subjects volunteered under an IRB approved gait study. The experiments were conducted on the Computer Assisted Rehabilitation ENvironment (CAREN) developed by Motek Medical. The CAREN is a state of the art testing environment that integrates a motion capture system with ten Vicon cameras, a split belt treadmill mounted on a 6 DOF motion base, and force plates to record ground reaction forces. To aid the motion capture, eight reflective markers were placed on every subject to record kinematic data, as shown in Fig. 1. The walking velocity for a subject's trials on the CAREN was recorded overground as an average of three trials of the 10-meter walk test, at the subject's normal walking speed.

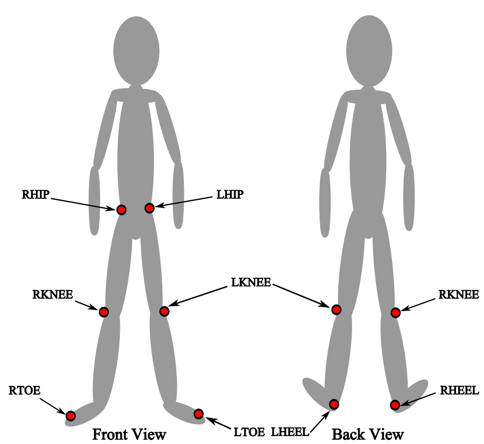

Fig. 1. Placement of the eight markers on the subjects.

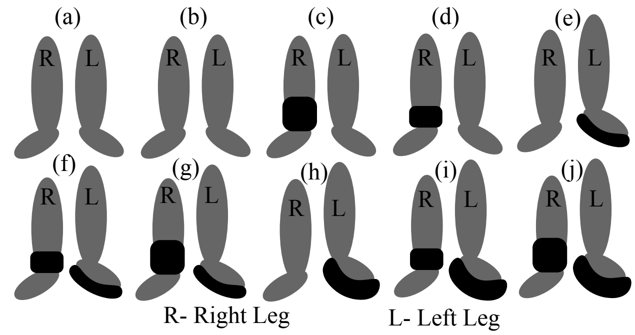

Fig. 2. The various perturbations utilized in the experiments (a) Baseline, (b) Second Baseline, (c) Big weight on dominant leg, (d) Small weight on dominant leg, (e) Small length on non-dominant leg, (f) Small weight and Small length, (g) Big weight and Small length, (h) Big length on non-dominant leg, (i) Big weight and Big length, and (j) Small weight and Big length.

Every subject walked for two minutes with each of ten perturbations. The two minute time period was chosen to allow the subject enough time to adapt to the changes, but short enough to prevent fatigue over the entire trial. Every perturbation is applied to a subject at random so as to not repeat the same pattern of perturbations for any subjects. The alterations were of two major types: change in leg length on the nondominant leg and the addition of mass at the ankle on the dominant leg. There were two levels of leg length: the small length of 0.027 m and the big length of 0.052 m shown in Fig. 2 (e) & (h), and the addition of an ankle mass: small mass of 2.3 kg and big mass of 4.6 kg shown in Fig. 2 (c) & (d). Some perturbations were a combination of change in leg length and the addition of ankle weights to observe the combined effects, shown in Fig. 2 (f), (g), (i), & (j). The subject had a baseline trial at the start and end of the session with no added height or weight to determine their unimpeded walking pattern.

IV. Gait Asymmetry Metric

A total of ten subjects were tested and the kinematics from the motion capture and kinetics from the force plates were collected. The analysis performed on the data is a proof of concept for this metric. Hence, five parameters were used in the analysis: step length and step time representing spatio/temporal parameters, and vertical ground reaction force, push off force, and braking force representing the kinetic parameters. The study did not include kinematic parameters in order to be comparable to the previous study [1]. However, the metric is designed to be versatile enough to accommodate all types of gait parameters in the form of symmetry indexes.

In order to calculate all the parameters, the data was organized into the number of steps taken based on the heel strike and toe off data. A step is characterized from heel strike of one foot to the heel strike of the opposite foot. Step length and step time are determined by using the difference of the left and right heel positions for each step. The ground reaction, braking, and push off forces were measured for each step according to the step interval. Braking and push off forces were measured at peak horizontal forces near heel

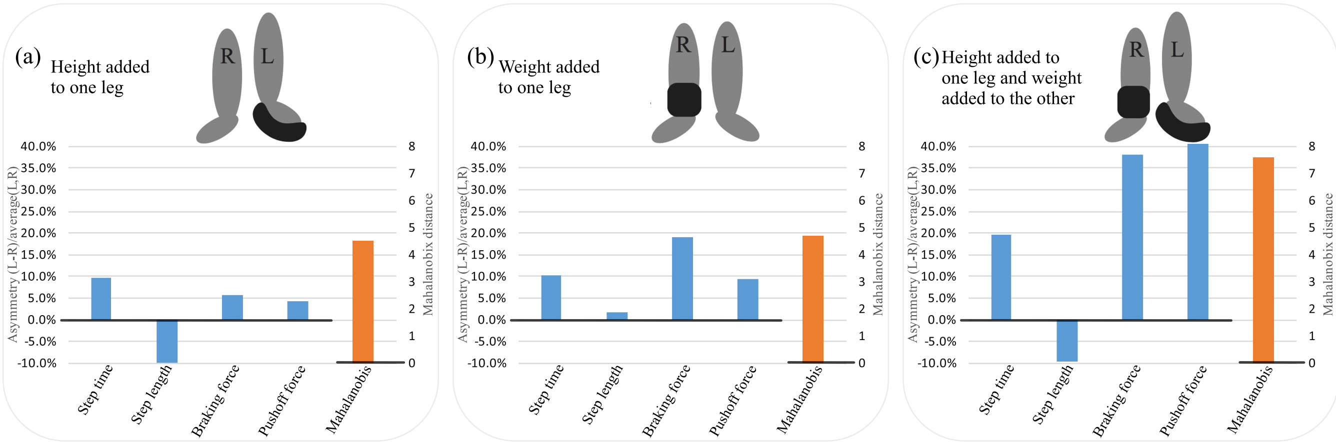

Fig. 3. Comparison of Perturbations and respective Mahalanobis distance metric. Gait asymmetry of step time, step length, braking force, and push off forces (a) Change in Leg Length, (b) Addition of mass, and (c) Combination of Leg Length and Addition of mass

strikes and toe offs. The amount of asymmetry is calculated in terms of percentages between the left and right instances of all five parameters.

The data containing the percentage of asymmetries is used to showcase this metric because it is mathematically straightforward to obtain and it scales the units of all the diverse parameters. We measure the distance between the points from perfect symmetry which is advantageous because it simplifies computation and gives a representation that can be visualized, and is similar to the approach taken by the CAI [18]. As the Mahalanobis distance is calculated, it takes the covariance of the high dimensional data into consideration. In this analysis we successfully obtained results for the five-dimensional data, however, this method can be expanded to much higher dimensional data in the future.

The Mahalanobis distance [19] in its normal form appears as in equation 1,

$$D = \sqrt{(Data-\mu) * inv(\Sigma) * (Data-\mu)'} \ , \quad (1)$$

where

- D = Distance from Ideal Symmetry
- μ = Mean of the Data
- Σ = Covariance of the Data.

The Mahalanobis distance is used to scale relative distances from the center of a high dimensional point cloud to all the points. The modified equation (2) loses the μ term because it is replaced with a zero vector representing perfect symmetry.

$$D = \sqrt{(Data) * inv(\Sigma) * (Data)'} \quad (2)$$

The Mahalanobis distance for our experiment is shown in Fig. 3 where the right bar in each subplot shows the magnitude of difference from perfect symmetry. A subset of the measured parameters are shown for comparison to demonstrate how they combine to affect the Mahalanobis distance. The deviation of each measure is scaled based on the variance within that measure, so measures that generally have larger magnitudes of asymmetry (i.e., forces) will be scaled so that each gait parameter has a similar influence on the overall metric. These weightings are a starting point

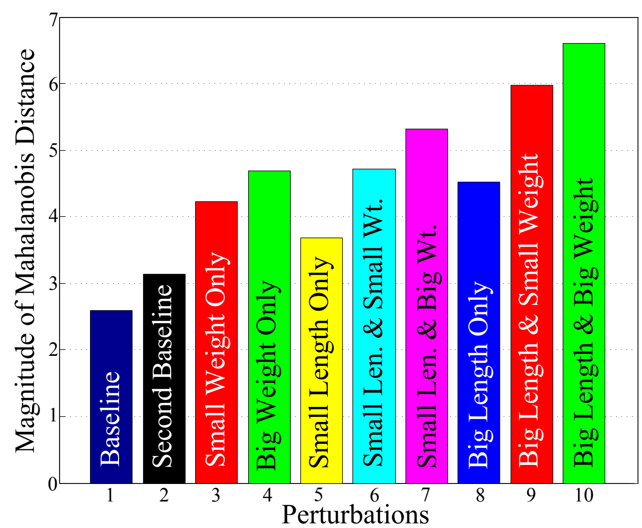

Fig. 4. The mean Mahalanobis distances of all perturbations from ideal symmetry.

and the weight assigned to each metric could be evaluated and adjusted based on the effect of each parameter on appearance [24] and based on the biomechanics related to which gait parameters are most important.

To understand the effects of the different physical alterations, the mean of all the Mahalanobis distances is taken for every perturbation averaged for all subjects as shown in Fig. 4. Perfect symmetry would be represented by a magnitude of 0, which is not expected, even in healthy individuals [25], and most subjects without any perturbation had a Mahalanobis distance of between 1-3. Baseline gait of all subjects as seen from Fig. 4 has some amount of asymmetry associated with it, showing that normal gait is not always symmetric on all gait parameters.

An interesting result from Fig. 4 is that asymmetry in a person's gait increases more with a change in leg length, δD = 0.46, as opposed to the addition of a mass at the ankle, δD = 0.85. This result is consistent with an earlier analysis of the same data using an analysis of the individual gait parameters [1]. The earlier study showed that a change in leg length disrupts more gait parameters, especially spatial and temporal parameters, than the addition of masses at the ankle [26], [27]. This is significant in terms of gathering the overall trend of asymmetric perturbations in a walking study.

V. Discussion and Conclusions

Using percentage of asymmetry of each step to obtain Mahalanobis distances to classify gait patterns, makes this metric distinctive. As discussed above, this can be easily expanded to include more kinematic and kinetic parameters, such as the various joint angles and moments. Future studies will include more gait parameters relevant to the type of study and anticipated effects that will further validate this metric. Another compelling use of this metric may be that it can be applied to subgroups of interest to find individual effects of the parameters on the total asymmetry of the perturbation. For example, all kinetic parameters can be compared to all kinematic parameters.

An important reason to have a simple metric is to estimate if asymmetric effects applied through rehabilitation techniques can bring about better symmetry among individuals with asymmetric gait. The results from this metric suggest that the combined effects of both leg length and addition of mass are bigger in magnitude than would be expected from a simple summation of their individual effects. This shows that the addition of an asymmetric effect counteracts a person's gait asymmetry and may improve their overall symmetry, but it would be difficult to return to a symmetry level similar to that of an able-bodied individual.

This metric can be used to evaluate any gait related study that uses symmetry to evaluate a patient's improvement. Further, evaluation will be conducted upon future studies with more asymmetric perturbations and devices that apply asymmetric effects on the subject's limbs. The addition of PCA and possibly employing machine learning, such as support vector machines (SVM), to automate the classification of data to obtain a clear picture of the effects of the various rehabilitation techniques on the symmetry of an individual's gait is a future goal. Unlike previous research, the studies will be aiming at simplifying the generation of gait metrics so that they can have widespread use, especially in physical therapy. Objectivity is required for evaluating pathological gait and quantitative gait metrics are the most reliable way of determining outcomes for a patient's rehabilitation and could possibly help in the choice of rehabilitation methodologies.

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