Evaluating and Optimizing Gait Enhancing Technologies Using a Virtual Reality Environment*

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Abstract: **The Center for Assistive, Rehabilitation, & Robotics Technologies (CARRT) at the University of South Florida is a multidisciplinary center that integrates research, education and service for the advancement of assistive and rehabilitation robotics technologies. This includes technologies that assess and improve mobility including for those with amputations, traumatic injuries, or stroke. Current research studies include using the state of the art CAREN (Computer Assisted Rehabilitation ENvironment) virtual reality system to assess outcome measures for prosthetics, to evaluate prosthetic technologies and assess related outcome technologies, to compare wearable sensors, to design rehabilitation devices, and to improve rehabilitation and training strategies. Amputation, stroke, and aging can lead to asymmetric and inefficient gait patterns that often lead to falls. This paper describes various methods used to evaluate and optimize gait-enhancing techniques using a virtual reality environment with preliminary results from several current projects.**

I. Introduction

The use of virtual reality (VR) enables researchers to assess a subject's gait in an environment that more realistically mimics everyday life compared to a typical gait laboratory. VR also allows for the introduction of visual, auditory, vestibular, and tactile inputs into a testing environment in a controlled and systematic way. An integrated VR environment capable of creating realistic scenarios allows researchers to investigate and optimize gait-enhancing technologies in a scientific way. The CAREN virtual reality system, which includes a spilt belt treadmill, dynamic platform and motion tracking capabilities, is currently used to test, assess and improve the gait of prosthesis users and crutch users by providing controlled virtual environments and real-time, continuous gait tracking.

II. Background

A. *Lower Limb Prosthetics*

In the United States, there are more than 2 million people who have lost a limb and that number is expected to double by 2050 [1]. On average the healthcare costs are $500,000 per person over a 5-year period following limb loss, and additional prosthesis costs over the 5-year period can reach $450,000 [1]. The prevalence and expenses involved in lower limb amputation necessitates specific and effective tools and outcome measures for prosthesis prescription, evaluation, and rehabilitation. Evidence-based and effective prosthesis prescription can lead to improved rehabilitation, quality of life and reduced healthcare costs.

Lower limb amputees are classified by the Medicare Functional Classification Levels (MFCL) on a five level scale of K0-K4, where K0 represents an amputee who cannot walk and oppositely, K4 represents an amputee whose capabilities exceed basic ambulation. These K levels [2] are based on "past history, current condition, status of residual limb, desire to ambulate, clinical assessment of potential based on experience and reasonable expectations of a prosthetist and physician. Records must document current functional capabilities and expected functional potential" [3]. Insurance companies use this scale to determine which types of prosthetic components will be covered at each level [4].

One of the main differences between functional levels is the ability to walk and navigate obstacles, particularly at varying speeds. The use of this scale is particularly evident in the prescription and coverage of microprocessor knees, where a K3 amputee can qualify for a microprocessor knee due to their ability to vary their cadence; however, a K1-K2 does not qualify because of a fixed cadence [4]. Stevens, among others, suggests that the current method of determining candidacy for a microprocessor knee based on variable cadence needs to be revised because the stumble recovery, obstacle navigation and increased stability features could also benefit amputees at the K2 level [5]. The AAOP State of the Science Conference identified the need to consider revising the method of determining microprocessor knee candidacy [6].

According to Passero, the prescription of prosthetic components is "fundamentally based on the projected or otherwise documented functional level and weight of the patient"; however, "the prescription criteria for both populations [upper and lower limb amputees] are dependent on factors beyond anatomic involvement or the level of deficiency" [3]. Gremeaux et al. also emphasized the absence of a universally accepted or evidence-based method for defining a patient's functional level and the appropriate prosthetic prescription [7]. While there are many outcome measures available, there is not a gold standard that is objective, scientific, and evidence-based [8-11], no guidelines exist on when or which tool to use for a specific purpose [9], and there is a lack of consensus on which tool is best for determining function and prescription [7, 11].

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Performance-based measures to evaluate lower limb amputees and their prosthesis use include the following: Amputee Mobility Predictor (AMP) [12], Comprehensive High-Activity Mobility Predictor (CHAMP) [13], Timed Up and Go (TUG) test [14], six minute walk test (6MWT) [15], two minute walk test (2MWT) [16], 10 meter walk test (10mWT), Berg Balance Scale (BBS) [17], L-Test of Functional Mobility [18], Hill Assessment Index (HAI) [19], Stair Assessment Index (SAI), Lateral Reach Test, Four Square Step Test, and Symmetry in External Work (SEW) [20]. The 2MWT and 6 MWT are frequently used, but only test walking on level ground. The CAREN virtual reality system with motion tracking is currently being used to create patient-centric assessment selection algorithms based performance measures described for clinicians to determine the optimal lower limb prosthetic prescription and function. In conjunction with the VR simulator, prosthetic simulators can be used to quickly test concepts on unimpaired individuals prior to testing on amputees. Such prosthetic simulators are used to evaluate an upper limb prosthetic simulator for kayak hand testing [21] and the optimal location of a prosthetic knee [22].

B. *Assistive Walking Devices*

In the United States, there are approximately six million people who use crutches for everyday mobility, and the number of individuals using assistive devices for mobility is growing more rapidly than the general population [23, 24]. However, this does not include partially-impaired persons using crutches as a supplement to other assistive mobility devices such as wheelchairs, scooters, or lower limb prosthetics [25]. While a crutch user may opt out of crutch walking to predominately use a wheelchair, the use of crutches encourages upright posture, remaining active, and more independence (maneuverability), all of which are highly beneficial for long-term health [26, 27]. Crutches are often used for people who cannot use their legs to support their weight for reasons ranging from short-term injuries (<6 months) to lifelong chronic disabilities.

Short-term injuries that may require crutches include acute conditions such as foot and leg sprains, fractures, tendon tears, hip and knee replacements, or other lower extremity injuries. Short-term crutch users mainly use a swing-through crutch gait where the user ambulates by pivoting over both crutches simultaneously. While this type of crutch walking pattern is the fastest crutch gait, it is the most energy consuming [28, 29]. Fatigue is one of the top hindrances in using crutches over longer distances, partially because crutch walking on level ground inherently carries a metabolic penalty 1.5 to 6 times that of normal walking[28].

Individuals with chronic impairments rely on their crutches for everyday ambulation, for example, lower limb amputation, spinal bifeda, cerebral palsy, muscular dystrophy, spinal cord injury, post-polio syndrome, osteoarthritis, or multiple sclerosis. Crutch ambulation for long-term lower-limb-impaired individuals offers partial preservation of lower-extremity function [27] . Many long-term crutch users rely on a more stable 4-point crutch walking style. When ambulating with this type of crutch gait, the crutch user always maintains three points of ground contact. They repeat a step pattern of alternating leg step, then crutch step. Stability is a prime concern in chronic crutch users, especially the progression down a decline, which can be dangerous. The loss of control during crutch walking down a decline can lead to unstable dynamics and falling in some cases. As a result, users descend slowly, diagonally, or avoid declines altogether because of a fear of falling [30, 31].

III. The CAREN Virtual Reality System

A. *Hardware*

The CAREN system (Computer Assisted Rehabilitation ENvironment) is a versatile, multisensory system for clinical analysis, rehabilitation, evaluation and registration of the human balance system (Figure 1). By means of unique software, MOTEK Medical integrates both existing and new technologies into research and medical solutions for orthopedic, neurological and rehabilitation use. The use of virtual reality (VR) enables researchers to assess the subject's behavior and includes sensory inputs like visual, auditory, vestibular and tactile. Inputs may be isolated or combined. The real-time feedback system registers and responds faster than human perception. The CAREN system is a unique integrated-reality environment capable of creating the highly realistic situation where researchers can investigate new ways and methods of encouraging patients. Based on the available sensor information, custom rehabilitation behaviors can be defined, utilizing the optimal treatment program.

B. *Software*

The CAREN system's D-Flow software allows the multiple components to be combined into one real-time device. The user's actions are defined as input and the various CAREN components are defined as outputs. The software interface is modular in design with inputs and outputs going from module to module through connections. Each module has a user interface for its parameters to be altered.

Gait software is available from Motek Medical including the Human Body Model (HBM), Gait Real-time Analysis Interactive Lab (GRAIL), and Gait Offline Analysis Tool (GOAT). The CAREN System with Vicon motion tracking has the capabilities to collect spatiotemporal gait parameters such as stride length, mean walking speed, stance and swing time, kinematic parameters such as knee flexion angle, trunk tilt, ankle pronation, and kinetic parameters that include hip, knee and ankle moments continuously in a controlled simulated environment.

The HBM, a musculo-skeletal model, allows for both visualization and calculation of muscle forces, joint angles, moments and powers in real-time during CAREN sessions. The subject measurements, marker and force plate data are input into the model, and inverse dynamics are used to calculate the biomechanical outputs. The HBM (Figure 2) can be displayed on the screen to represent the patient in the virtual reality environment and as muscles are activated, the

Figure 1. The CAREN system

muscles will light up and change colors depending on the amount of force produced. GRAIL is gait analysis tool that provides real-time gait parameters and feedback to the patient and clinician, which allows for immediate adjustments to gait and balance during the training sessions. The GOAT provides a clinical gait report following sessions; including average gait parameters, standard deviations and graphs, as well as a comparison between the right and left sides, and to a set of normative data.

IV. ASSESSING AMPUTEE GAIT

A. Evaluating Outcome Measures for Lower Limb Prostheses

In a previous study conducted at USF's typical motion capture laboratory, the C-Leg and the Genium knee prostheses were compared on ramps and stairs instrumented with two force plates. This study showed that the Genium knee improves knee kinematics closer to non-amputee values as compared to C-Leg. While comparisons such as these are useful, the ultimate utility is limited. That is, we attempted to analyze our data to provide some psychometric analysis of the hill assessment index. We were able to assess reliability of the instrument [19]. Conversely, we were unable to compare step length from our motion analysis data. That is because subjects were targeting the force plates and altering their stepping pattern and thus confounding our attempts to conduct criterion validity analyses. Because the CAREN system has a kinetic instrumented treadmill that can tilt in the sagittal plane, this situation will be greatly improved and enable the validation analysis not possible with a conventional, static force plate instrumented motion analysis laboratory.

An initial testing protocol was approved by the University of South Florida's Institutional Review Board to collect data with the CAREN system while non-amputees and amputees walk on a treadmill in the mountain road scene at a self-selected speed on level ground, up-hill and downhill, side-hill on the intact side, side-hill on the prosthesis side. Preliminary data from two non-amputees has been collected and analyzed. Gait trials were collected for walking on level ground, 5 and 10 degrees uphill and downhill, and a 5-degree side hill.

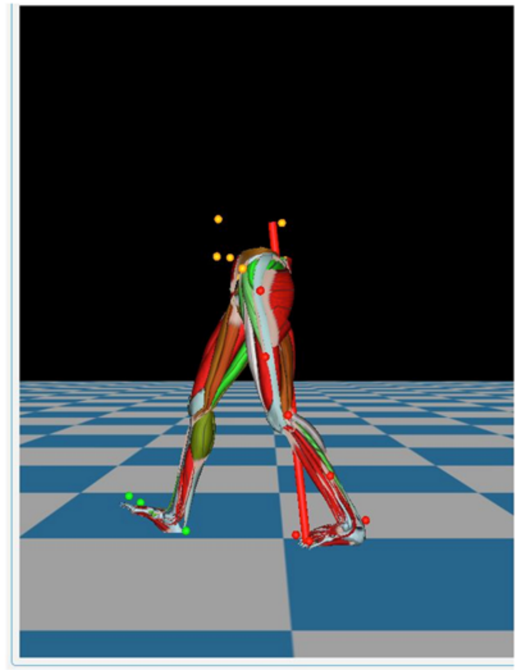

Figure 2. The Human Body Model (HBM) that can be displayed on the CAREN system screen

The kinematic analysis at each elevation, including the mean minimum and maximum angles and standard deviation for the five subjects, is presented below in Table 1. As would be expected the values differ at each elevation; however the +/- cross slopes are relatively similar as these were healthy subjects with no apparent gait asymmetries. A comparison amongst the elevations showed the maximum knee flexion occurred with decline gait, whereas the maximum hip and ankle flexion angles occurred with incline gait. The differences between the maximum at each elevation were approximately 5° for knee and ankle flexion; however, the difference in maximum hip flexion was about 15° between incline and decline. Knee, hip and ankle flexion at initial contact and throughout the stance phase were also significantly greater for incline gait. Figure 3 shows the average ankle dorsiflexion and plantar flexion of subjects walking on the CAREN system simulating various elevations. This analysis is consistent with other literature. Similar data from prosthetic users can be used to evaluate and prescribe lower limb prostheses.

This preliminary work will lead to the evaluation of existing outcome measures using the CAREN virtual reality system with motion tracking and create patient-centric assessment selection algorithms for clinicians to determine the optimal lower limb prosthetic prescription and function. The 6MWT, HAI, SEW and PEW will be the first conventional prosthetic outcome measures that will be

Kinematics	Elevation	Min. Angle (Degrees)	Max. Angle (Degrees)	Std. Dev. (Degrees)
Knee Flexion/Extension	Level	1.1	58.5	19.1
	Incline	3.9	56.5	15.9
	Decline	2.6	60.8	18.0
	+ Cross Slope	3.3	57.9	18.1
	- Cross Slope	2.7	57.0	18.0
Hip Flexion/Extension	Level	-6.3	33.5	14.1
	Incline	-5.9	45.0	17.8
	Decline	-4.7	29.9	12.5
	+ Cross Slope	-6.8	33.8	14.3
	- Cross Slope	-6.3	33.7	14.6
Ankle Dorsi/Plantar Flexion	Level	-7.5	21.0	7.4
	Incline	-3.8	24.5	7.4
	Decline	-3.3	22.7	7.2
	+ Cross Slope	-6.0	21.4	7.2
	- Cross Slope	-6.0	20.8	7.1

Table 1. Kinematic analysis of five healthy subject walking on the CAREN system are various elevations

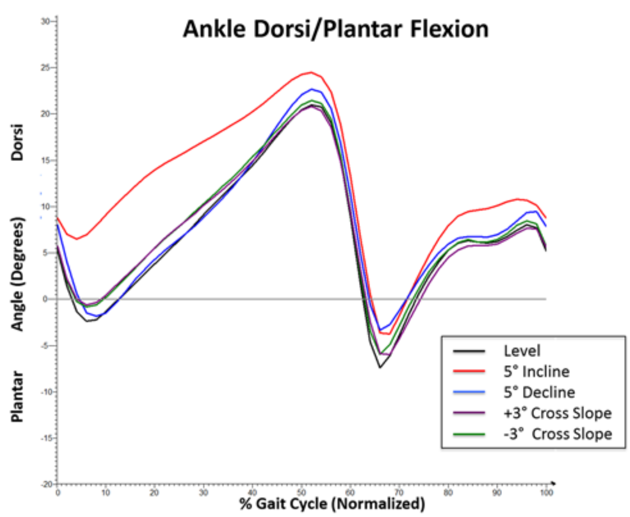

Figure 3. The average (n=5) ankle angles of subjects while walking on the CAREN system simulating level, uphill, downhill and side slope.

simulated and tested on the CAREN system. Based on the CAREN system's ability to provide continuous gait analysis, the ability to alter the visual and other sensory stimuli, the determination of key outcome measures needed to evaluate and classify lower limb amputees and prosthetic components will be completed. A testing protocol will be implemented for psychometric (i.e. reliability, repeatability, validity, sensitivity) analysis of outcome measures. An algorithm will be developed to improve the implementation of outcome measures for optimized amputee care.

B. *Lower Limb Impairment Simulators*

Wearing a prosthesis affects gait in several ways, such as changing the passive dynamics of the prosthetic leg compared to the intact leg, changing the amount of propulsive force from each leg, and changing the stiffness of the joints. Each of these changes causes some asymmetric alteration in the gait. To understand how each of these factors affects the gait, we use a prosthetic simulator. The prosthesis simulator [22, 32] functions similar to existing passive prostheses, but fits over an intact knee. The difference is that non-amputees wearing the prosthesis simulator will have an extra mass from their shank that protrudes behind them. Similar dynamics with the large extra mass can be realized by shifting the moment of inertia of the prosthetic shank.

The prosthetic simulator was used in one set of experiments to examine the effect of prosthetic knee location on gait patterns. When wearing a transfemoral prosthesis, the mass and strength of the two legs are not equal, and there are fewer biomechanical reasons to keep the prosthetic knee location the same as the intact knee. The hypothesis is that moving the prosthetic knee location can beneficially affect the gait by balancing the motions and forces. The hypothesis is justified based on tests with a passive dynamic walker model that shows a prosthesis 40% lighter than the intact leg with a knee location moved down the leg by 15% can have symmetric step lengths [33] .

The experiments, described in detail by Ramakrishnan[22], had individuals walk on the prosthetic simulator with the prosthetic knee at different heights. These initial results, shown in Figure 4, show that the step length and swing time are more symmetric for lower (i.e., closer to ground) knees and worse as the knee approaches the contralateral knee location. This demonstrates that lower knees may be better in certain cases, but the mass distribution of the prosthetic leg is distinctly different in this case since the entire existing leg and the prosthetic simulator mass are affecting the gait.

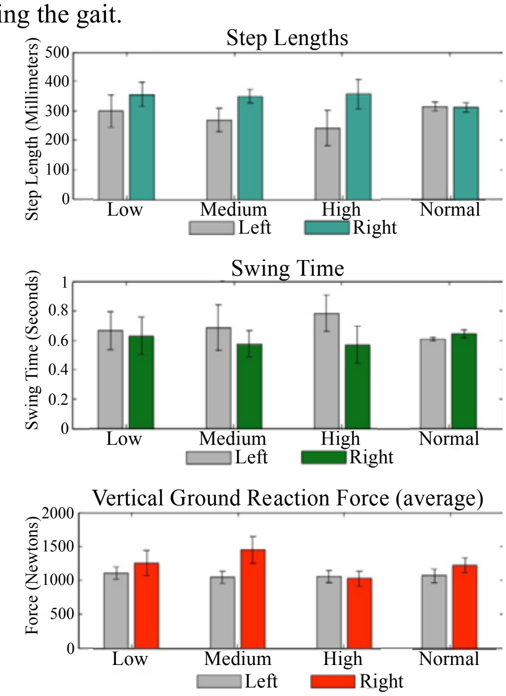

Figure 4. Results from walking on the prosthesis simulator (data adapted from Ramakrishnan, [22]. Low is 7 inches (19%) below standard knee height; medium is 5 (14%), high is 3 (8%), and normal has no simulator.

V. EVALUATION OF CRUTCH DESIGN

The CAREN system was also used to evaluate new crutch tips that interface with the ground to provide assistance. The kinetic crutch tip (KCT) [34] uses a specially designed curve based on a kinetic shape [35] that converts the downward force from walking into an assistance force that helps to propel the user forward. One way to think about this assistance is that it moves the equilibrium point of a crutch from being straight up to being at an angle, so that the crutch will seemingly rotate against gravity (see Figure 5).

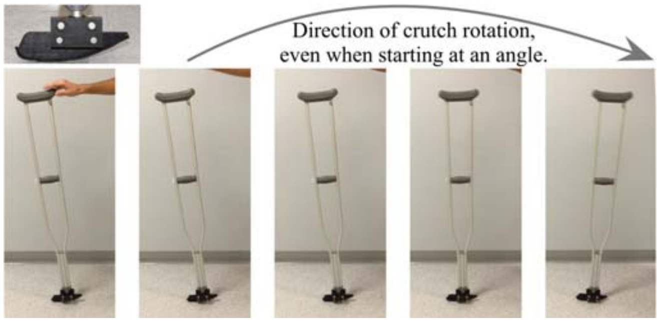

Figure 5. Crutch motion shown over one second. The Kinetic Crutch Tip changes the equilibrium point so that the user does not have to push off as hard to swing over the peak of the crutch, thus using less energy.

Moving the crutch equilibrium point provides an assistance force, which reduces the effort needed and hence reduces the fatigue and stress-related pain, which are two of the most common issues associated with crutch walking. The study by Capecci et al. [34] used the CAREN system to examine the forces and motion while walking on two different KCTs and compared the gait patterns to walking on standard crutch tips. They found that the horizontal ground reaction forces that were resisting forward motion were reduced by up to 74% compared to using a standard crutch tip. They also found that the peak vertical force of the heel strike was reduced by up to 27% using a different KCT. Future work on the crutch tips will examine different shapes and how the assistance can benefit gait when walking up and down hills (example shown in Figure 6).

Figure 6. Future experiments will use the CAREN to examine how the Kinetic Crutch Tip can assist a user to walk up and down slopes.

VI. FUTURE DIRECTION

Quantitative assessments of gait enhancing technologies are necessary to properly evaluate and optimize them. The state of the art CAREN virtual reality system offers a repeatable systematic framework providing a quantitative way to aid researchers in rehabilitation and gait augmenting technology. To continue making scientific advances in gait rehabilitation that are repeatable and to make comparisons between studies easier, more standards should be established with consistent benchmarks across studies. Some benchmarks have been proposed [36], but the related scientific and industry communities need to jointly be behind them to make them effective.

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