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Using Ambulatory Virtual Environments for the Assessment of Functional Gait Impairment: A Proof-of-Concept Study

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1. Introduction

Virtual reality (VR) is appealing for gait assessment/rehabilitation [1-4]. Locomotor behavior has been suggested to be consistent between physical and virtual environments [5,6]. This is important for gait assessment/rehabilitation using VR to adequately transfer to real life locomotion.

Before VR's potential can be fully exploited for gait rehabilitation, it is critical to develop assessment tools providing a quantitative description of functional mobility. For example, there are no generally accepted quantitative measures for assessing gait deficits and responses to treatment following anterior-cruciate ligament (ACL) injuries. The relationships between clinical assessment methods and functional gait are thus unclear and many questions remain as to the indications for, and results of, ACL reconstruction.

Self-report measures are used for joint-specific, mobility, and quality of life indicators (KOOS, Dynamic Gait Index and SF-36 [7-9] respectively). These tools have been validated, but their use means accepting inherent subjectivity. The one-legged hop test and the 6 m shuttle run [10] are more quantitative in nature. However, the unclear transfer to walking function for the former or the inability to capture spatial information for the latter have raised concerns regarding their validity for assessing walking deficits. Developing tools providing a quantitative description of functional gait and bridging the gap between localized evaluations (e.g. joint level) and subjective patient input regarding their mobility is therefore warranted.

Sophisticated treadmill/screen-based VR systems have been implemented for the purpose of gait rehabilitation [11,12]. Such systems provide no or limited possibility for steering the body in a new walking direction failing to capture an integral part of safe locomotion: circumventing obstacles [5,6,13-16].

Previous unpublished pilot work using a figure-8 walking test around two physical posts showed larger turn areas with faster walking speeds or slower speeds with similar turn areas as a natural response to an emulated lower limb disability. Some participants, however, coped

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with the disability by combining the two strategies. This prompted designing an experiment allowing the independent control of turning speed/area while measuring the other as a gait impairment indicator. VR is well suited for this task as it allows for precise measurement of path geometry/walking speed while providing control of the performance parameters in a way that would be impractical or impossible in physical environments.

This study was undertaken to demonstrate the sensitivity of VR to detect global functional gait impairment resulting from lower extremity disabilities as a prelude to describing mobility changes following injury/treatment. An emulated knee disability was used to provide a proof-of-concept and propose a protocol enabling a quantitative characterization/detection of mobility deficits. Using VR to control task parameters with quasi-instantaneous feedback and measuring temporal/spatial variables for assessing locomotor capacity solely tracking global body motion is novel. It was hypothesized that testing the natural response (pathway geometry/walking speed) to the emulated disability as well as the response to path/speed manipulations would lead to the successful detection of mobility impairment.

2. Methods

2.1. Subjects/Instrumentation

Eleven adults (Table 1) provided written informed consent and participated in the study. Ethics approval was obtained from the Brown University review board. Participants were studied at baseline function and after an emulated lower extremity disability (knee splint preventing normal knee flexion in gait).

The experiment was conducted in the VENLab, a 12×12 m room allowing free over-ground walking while viewing a computer-generated virtual environment in a helmet-mounted display (SR80A, Rockwell Collins, USA). Three-dimensional positions/orientations of the subject's head were tracked at 50 Hz (IS-900, Intersense, USA) and used by control software (Vizard, WorldViz, USA) to update the virtual scenes in real-time (67 ms latency).

2.2. Procedure

Leg dominance was assessed [17] and participants practiced walking with the splint before the VR test. Following a five-minute VR familiarization (splint-free navigation), participants walked a figure-8 course around two virtual posts (0.2×2 m) placed 6 m apart (Fig.-1A). The figure-8 course allowed testing both turning directions (each with a different leg inside the turn) in each lap.

Three disability conditions were used: No splint (NO), splint on Dominant (DO) and Non-Dominant (ND) leg. Three walking scenarios were used: Natural, Controlled Speed (CS), and Controlled Path (CP). Participants first performed the Natural scenario involving figure-8 walking at self-selected natural speed without feedback mechanism. In the CS scenario, participants maintained a speed at or above their own natural speed (measured during the Natural scenario) throughout all portions of the course (including turns) while path geometry was measured. In the CP scenario, participants walked through virtual path markers hanging at sternum height to preserve natural dynamic posture (Fig.-1B) while speed was measured. Participants performed two CP trials i.e. with the dominant/non-dominant splinted leg on the inside of the smaller loop.

Exploiting VR, automatic online auditory feedback ensured that the target speed/path was maintained throughout the locomotor performance for the CS/CP scenario. Feedback algorithms respectively provided auditory warning while participants had velocities below their own mean Natural walking speed minus 20% or current positions outside +/-10 cm of the prescribed path. The minimum velocity threshold was set to Natural speed minus a margin

accounting for the natural sudden velocity drop with each step (determined to be approximately 20% for unconstrained walking during pilot work). The presentation order of the CS/CP scenarios was counterbalanced between participants.

2.3. Data analysis

Participants completed seven laps per trial and the middle five were analyzed. Path data were filtered (Butterworth, 2nd order, double-pass, 6 Hz) and turn speed/area above/below longitudinal axes $Z=5.25/Z=0.75$ m (Fig.-2a) were calculated using custom MATLAB programs. Statistical analyses included ANOVAs (SPSSv16.0) and Tukey pairwise comparisons between the three disability conditions. For the CP scenario, only the turns for the smaller, more challenging loop were analyzed.

Following the group analysis, a subject-by-subject deficit detection criterion was applied for each walking scenario. Subjects were deemed to exhibit a deficit in a given walking scenario when the amplitude of their own change with the emulated disability was at least within one standard deviation of the mean group change for this particular walking scenario.

3. Results

Dominance of the splinted leg (all three tests) or whether it was on the inside of the turn (Natural & CS tests) did not influence performance. The Natural scenario (using both figure-8 loops) revealed different adaptive strategies for coping with the emulated disability: maintaining turning speed while altering path geometry; decreasing turning speed while maintaining path geometry; and combining the previous two strategies. This resulted, on average, in a decreased turning speed (Fig.-2, $F_{1,53}=40.60$, $p<.001$) and an increased turning area ($F_{1,53}=5.98$, $p=.005$).

The CS scenario (both figure-8 loops) resulted in an even greater increase in turn area ($F_{1,53}=8.38$, $p=.001$) while the CP scenario (smaller loop only) consistently led to a speed decrease ($F_{1,20}=9.08$, $p<.002$) when coping with the disability.

The subject-by-subject deficit detection analysis occasionally returned false negatives for individual subtests depending on the coping strategies. However, when considering the overall test (each line across the three scenarios, Table 2) locomotor deficits were correctly detected in all subjects.

4. Discussion

As expected, participants coped with the emulated disability using different locomotor strategies in terms of turn speed/path geometry. It was also qualitatively observed that some participants circumducted the affected limb while others used hip hiking for proper toe clearance. This reflects the broad spectrum of natural adaptive behaviors generally observed following injury. For instance, some people exhibit a flexed knee gait following ACL rupture while others don't [18,19]. Relying solely on local variables such as knee range-of-motion to assess walking deficits could therefore overlook an existing impairment at the more global, functional, mobility level. Mobility assessments must therefore use quantitative global outcome measures that are more representative of the actual locomotor capacity.

The protocol introduced here exploits the mechanistic relationship between walking speed and path geometry to characterize the extent of mobility impairment by measuring the walker's global motion. Results suggest that measures in both the time and space domains should be considered for developing quantitative mobility assessment tools. These tools should not only rely on measuring natural behavior, but also on challenging the locomotor system in a way highlighting existing locomotor deficits regardless of the coping adaptive strategy.

The present protocol used VR to manipulate turning speed/area while the other was measured as a gait impairment indicator. Such manipulations including automatic online feedback would be difficult to achieve in a physical environment. The Natural scenario revealed that increasing turning area is indicative of an impairment caused by the emulated disability. The CS manipulation amplified this effect, which could theoretically increase the sensitivity of a tool using similar principles to detect deficits. The CP manipulation provided more consistent speed reductions in more subjects, which could theoretically augment the reliability of a tool using such principles. The fact that leg dominance/turn direction did not influence performance suggests that this protocol would be useful for characterizing deficits in ACL-injured patients regardless of their injury side (or that the test in its current form was not sensitive enough to detect small differences with leg dominance/turn direction). Further research should clarify this.

The developed protocol produced a series of individual subtest results which provided, when assembled (Table 2), a mean for correctly detecting locomotor deficits on a subject-by-subject basis regardless of their adaptive strategies. This protocol thus uses three different subtests acting as intertwined filters for an increased sensitivity in detecting mobility deficits. Applied to pathological populations, this VR walking protocol would also reduce the risk of aggravating injury by tripping over obstacles that are not physically present.

This study demonstrated that VR can be used to detect and quantitatively characterize mobility impairment with an emulated disability. It introduced a new avenue for bridging the gap between localized evaluations (e.g. at the joint level) and subjective patient input with regards to mobility function. This proof-of-concept study and the proposed VR protocol can be refined/ further developed to include tasks sensitive to other impairments. Broader implications include developing diverse clinical applications of VR to a range of other musculoskeletal/neurological disorders: to characterize disabilities, make the indications for interventions more objective, assess the outcome of reconstructive and rehabilitative therapies, and even design and assess prostheses.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Figure 1. Virtual environments used for (A) the Natural and Controlled Speed scenarios and (B) the Controlled Path scenario.

Figure 2. Group means for Path Geometry (A), Turning Speed (B) & Turning Area (C). Square brackets indicate significance ($p < 0.05$) and error bars are standard errors of the means. $N = 11 \times 2$ turns for Natural and Controlled Speed scenarios and $N = 11$ turns for the Controlled Path scenario.

Table 1

Subject characteristics

<u>Young Adults (6 women, 5 men)</u>			
	Mean	SD	Range
Age (yrs)	22.5	4.5	19 - 32
Mass (kg)	63.7	4.6	55.4 - 70.3
Height (m)	1.73	0.07	1.64 - 1.87

Note: Subjects reporting no neurological/musculoskeletal problems for the two-year period preceding the test.

Table 2

Detection of deficits on a subject-by-subject basis

Subject #	Natural	Controlled Speed	Controlled Path
1	X		X
2	X		X
3	X	X	X
4	X	X	X
5	X	X	X
6	X	X	X
7		X	X
8	X	X	
9	X	X	X
10	X	X	X
11	X		X

Note: X marks indicate a deficit i.e. an individual change with the emulated disability within one SD of the mean group change.