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LOCOMOTION STABILITY ADAPTATION TO THE VIRTUAL REALITY INDUCED SENSORY CONFLICTS

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ABSTRACT

Topic: Sensory system conflicts caused by virtual reality immersion may lead to alteration and adaptation in gait characteristics. The current study investigated such effect from the aspect of dynamic stability during walking. **Experiment**: Twelve healthy elderly took a one-minute treadmill walking experiment. Participants were randomly assigned to regular walking (RW) and virtual reality (VR) walking conditions. **Data Analysis**: Gait parameters were extracted from the kinematic data. Dynamic stability quantified by the maximum Lyapunov exponent was computed with both the embedded state space and the natural state space for six locations at lower extremities. **Results**: With the natural state space, the VR group was less stable than the RW group ($p<0.0001$). Joint instability increased with its vertical distance to the body COM ($p<0.0001$). The VR group's medio/lateral distance between ankles contained more high frequency and small amplitude fluctuations than the RW group, which may contribute to the instability of their gait cycles.

INTRODUCTION

The virtual reality (VR) technology is emerging in gait rehabilitation [1, 2]. Helpful as it might be, the virtual reality experience is still not exactly the same as what we sense in the real world. Postural and gait alteration with VR immersion has been sparsely reported [3].

Human locomotion has been considered at least a partly chaotic system [4], thus the dynamic stability as measured by the maximum Lyapunov exponent (maxLE) reveals an important property of the neural-motor control. Since VR immersion may cause sensory conflicts [3], it actually alters the inputs of the central nervous system and may be reflected in the motor control performance. However, the linkage between VR immersion and locomotion stability has not been thoroughly examined and requires further investigation.

METHODS

Experiment: Twelve healthy elderly participated in the study. They were randomly assigned into two equal groups. The regular walking (RW) group took a one-minute treadmill walking test at their normal speed. The virtual reality (VR) group took the same test but wore a virtual reality goggle during walking. The goggle provided a 3D dynamic scene of a downtown street, which evolved with time to match the subject's walking speed. For both groups, a ProReflex motion capture system (Qualysis Medical AB, Gothenburg, Sweden; 100Hz) was used to record 3D positions of six lower extremity markers: both ankles (at lateral malleolus, LA and RA), both knees (at lateral condyle, LK and RK) and hip joints (at ASIS, LH and RH).

Gait Characteristics Computation: Firstly, the 3D position data were filtered by a Butterworth low-pass filter (4^{th} order, cutoff 6Hz). Next, step length (SL) and step width (SW) were estimated by the distance between LA and RA markers in the anterior/posterior and medio/lateral direction respectively. COM vertical displacement (COMvd) was estimated by the average vertical displacement of LH and RH markers. 3D linear velocities of the markers were also calculated from the position data (both raw and filtered).

Dynamic Stability Computation: 3D positions and velocities were first combined to construct a natural state space with six dimensions (raw/filter-SSn). Next, velocity in each axis was used to reconstruct an embedding state space respectively (raw/filter- SSx, SSy and SSz). Time delay was selected as 20 samples using the average mutual information method [5]. The false nearest neighbor method indicated an embedding dimension of five [6]. However, to be consistent and comparable to SSn, the embedding dimension was eventually selected as six. MaxLE were computed using Rosenstein's algorithm [7] and performed in MATLAB R2007a (The MathWorks Inc., Natick, MA, USA).

Statistical Analysis: Group and marker difference in maxLE, group difference in gait parameters were examined using the ANOVA tests and performed in SAS JMP 8.0 (SAS Institute Inc., Cary, NC, USA).

RESULTS

With a three-way (groups, types of state spaces, marker locations and their interactions) ANOVA model, the VR group was found to have significantly greater maxLE than the RW group ($p<0.0001$). When examined separately for each type of state space, significant difference between RW and VR in maxLE was found for all the markers using filter-SSn. Raw-SSn found significant differences at both ankles and knees. Raw-SSx indicated significant differences at LA, RA and RK. However, for all the other state spaces, no significant group difference was found for any markers (Tab.1).

TABLE 1. SUMMARY OF MAX_LE VALUES

		LA	RA	LK	RK	LH	RH
raw	RW	.60±.15 *	.50±.11 *	.49±.11 *	.41±.08 *	.35±.11	.35±.13
SSn	VR	.78±.08	.72±.14	.65±.04	.65±.07	.45±.11	.47±.11
flter	RW	.98±.21 *	.85±.17 *	.74±.16 *	.64±.11 *	.52±.14 *	.49±.11 *
SSn	VR	1.26±.12	1.28±.18	.96±.11	.97±.08	.77±.14	.72±.14
raw	RW	.59±.19 *	.53±.17 *	.54±.17	.43±.08 *	.41±.17	.41±.11
SSx	VR	.86±.06	.81±.13	.69±.09	.71±.07	.35±.07	.32±.08
raw	RW	.25±.07	.20±.05	.28±.07	.24±.05	.34±.20	.34±.13
SSy	VR	.20±.02	.20±.04	.22±.05	.20±.04	.31±.07	.27±.06
raw	RW	.59±.17	.48±.10	.46±.15	.37±.07	.40±.17	.42±.12
SSz	VR	.64±.10	.60±.16	.37±.04	.44±.05	.34±.08	.38±.11
filter	RW	1.32±.29	1.29±.14	1.00±.16	.89±.11	.75±.17	.73±.09
SSx	VR	1.35±.20	1.21±.11	.92±.12	.96±.11	.71±.21	.71±.12

Across all the state space construction methods, maxLE was steadily decreased (meaning increased stability) from ankle to hip ($p<0.0001$) (Fig.1).

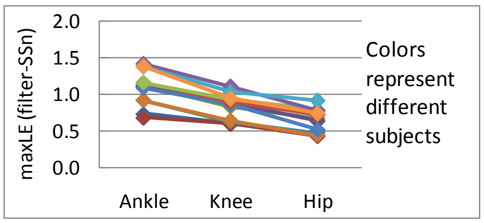
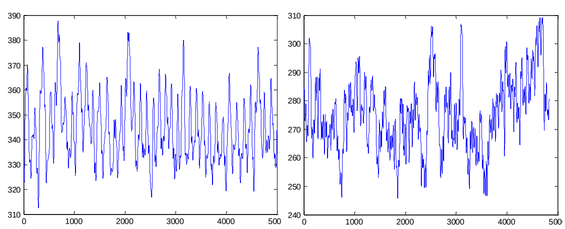


FIGURE 1. ENSEMBLE OF MAXIMUM LYAPUNOV EXPONENTS AT DIFFERENT LOCATIONS

No significant group difference of SL, SW and COMvd was found. However, the VR group's ankle distance in the medio/lateral direction (which was used to compute SW) appeared to contain more high frequency, small amplitude fluctuations than the RW group (Fig.2).



(a) RW (b) VR

FIGURE 2. MEDIO/LATERAL ANKLE DISTANCE

DISCUSSION

The results demonstrate significant degradation in dynamic stability with VR immersion. This is not unexpected considering the important roles of sensory inputs in regulating gaits. On one hand, this effect should be taken into consideration in the design of locomotion training systems or interventions which employ the VR techniques. On the other hand, instead of turning off one sensory system, this study provides a feasible method to alter interactions between sensory systems so as to study their effects on motor control. Meanwhile, the finding of decreased stability from hip to ankle is consistent with the results of our previous study [8], which again suggests that dynamic instability can be moderated with multi-linkage structure of lower extremities so that the upper body and the head are protected. This is similar as the mechanism of moderating vertical vibration during walking [9].

From the methodological perspective, state space constructed by multi-dimensional data appears to perform better than the embedding state space when the length of the time series data is quite limited.

This study demonstrates the effect of VR induced sensory conflicts on locomotion control but was not able to quantify how deep the subject was immersed in the virtual environment or the level of the conflicts.

CONCLUSIONS

The study investigated locomotion stability adaptation to the virtual reality induced sensory conflicts. The VR immersion experience was found to have a negative effect on lower extremities' local dynamic stability among the elderly, suggesting the importance of interaction between sensory systems in regulating gaits.

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