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Performance of a remote eye-tracker in measuring gaze during walking

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***Abstract* – Combining virtual environments and eye-tracking can provide insights about the relationship between gaze and gait in people at high risk of fall. Remote eye-trackers can estimate gaze while the head moves within a limited workspace, but several factors can influence accuracy and precision. This study aimed at assessing the performance of a remote eye-tracker both during controlled head movements and walking on a treadmill, while the visual stimulus moved on the screen. The head range of motion during gaze estimation was determined. The distance from the eye-tracker influenced data accuracy and precision of gaze estimation, while the target location was not a critical factor. The best accuracy was achieved at 650 mm from the eye-tracker (11±3 mm) and, during walking. Gaze fixations hitting static and moving objects were counted during standing (87 to 93 %) and walking (85 to 98 %), providing promising results for applications in virtual environments.**

I. INTRODUCTION

Diagnostic eye-tracking techniques have been used to explore the visual behavior during walking in populations at high risk of fall [1]–[4]. Several studies have shown that the visual decline could affect the ability to detect and negotiate hazards in the environment, contributing to poor obstacle negotiation [5] and to an increase of risk of falls [6]–[8].

Recently, virtual reality (VR) applications have been proposed to simulate challenging environments, including obstacles and distractors [9]. The integration of VR, kinematics and eye-tracking analysis allows investigating the relationship between the point of gaze (PoG) and the stepping accuracy in a safe, highly controlled and customized experimental set-up.

The ocular movement can be analyzed in terms of gaze fixations and saccadic movements. These movements can be identified through the analysis of the PoG [10]. The PoG can be estimated using eye gaze trackers (ETs). These can be either desk or head -mounted (remote or wearable) [11]. Although remote ETs are usually less accurate than wearable ones, they are better tolerated by the subjects [10, 11] and, therefore, they are more promising rehabilitation tools to be employed in VR based rehabilitation programs.

In general, when remote ETs are used the subject's head is expected not to move [10]. Their performance is influenced by their distance from the subject's eyes. According to the manufacturer specifications, remote ETs can also be used to analyze gaze in the presence of head motion within a limited workspace. However, in the latter case, the remote ET performance can be affected by several additional inaccuracy factors, such as the head motion, and the location of the visual target. These factors determine the limit of usability of the ET and they may influence both precision and accuracy of the PoG estimation. Moreover, the magnitude of the systematic and random errors affecting the PoG measurements would influence the identification of areas of interest (AoIs), defined as regions included in the visual stimulus from which gaze related information is extracted [10].

The aim of the present study was to assess the performance of a commercial remote ET [12] under various experimental conditions to evaluate its use in applications based on the combined use of treadmill and VR. Specifically, we evaluated the volume of trackability allowed by the ET and how the distance between the subject and the ET and the spatial location of the visual stimulus influence the quality of the PoG estimates. The tests were carried out on four subjects both during standing and walking.

II. MATERIALS AND METHODS

Four healthy volunteers (age: 33.5±5 y.o., height: 1.76±0.09 m) took part in the study. They were not affected by any oculo-motor deficit and did not wear lenses nor glasses during the experimental session.

A desk-mounted ET (Tobii, TX300, sampling frequency: 300 Hz) was employed to record PoG data. According to the manufacturer specifications, the ET allowed head movements (±150 mm along the anterior-posterior –AP– direction and ±100 mm along the medio-lateral –ML– and vertical –V– directions) with respect to a reference distance of 650 mm and anatomical head orientation. The ET was placed on an adjustable tripod in front of a treadmill (Fig. 1). A monitor (47-inch LCD, 1280×1024 px), attached to the wall, was used to display the visual stimuli. The ET and the monitor were centered with respect to the treadmill. While the participant was standing on the treadmill, the ET was adjusted to center

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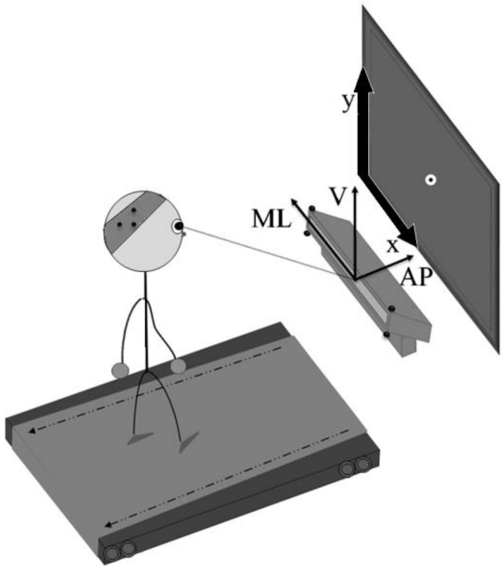

Fig. 1. Experimental set-up including markers (black dots).

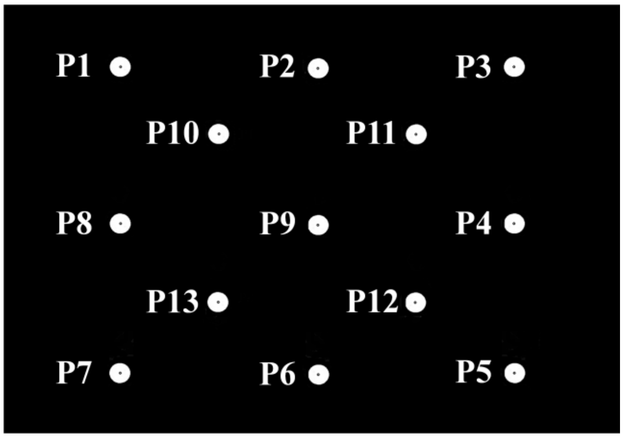

Fig. 2. The 13 dot-grid used to display the dot target in st550, st650, st750, walk1 and walk2.

his/her eyes.

The subjects' head was instrumented with three retro-reflective markers attached laterally to a headband. Four markers were attached on the ET edges (Fig. 1).

A six-camera stereo-photogrammetric system (Vicon, T20, sampling frequency: 300 Hz) was used to track the head motion. The cameras were placed so that potential infrared interferences between the two systems could be limited.

A. Protocol

As advised by the ET guidelines, acquisitions were performed in a darkened room and the reference distance between the subjects and the ET was set equal to 650 mm. For each participant, a subject-specific calibration was performed using the proprietary software

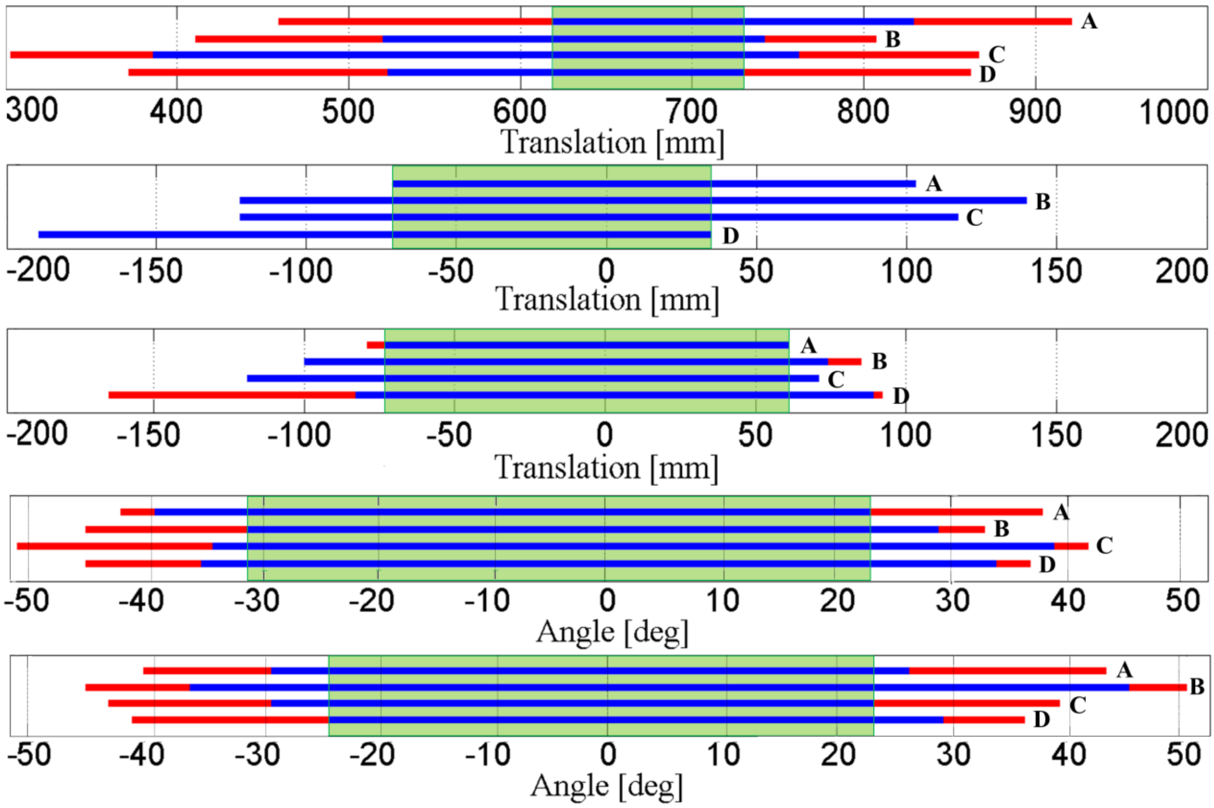

Fig. 3. The range of motion (red), the volume of trackability (blue) and the VoT (green highlight) are reported for each subject (A, B, C and D) in tasks tAP, tML, tV, rML and rV.

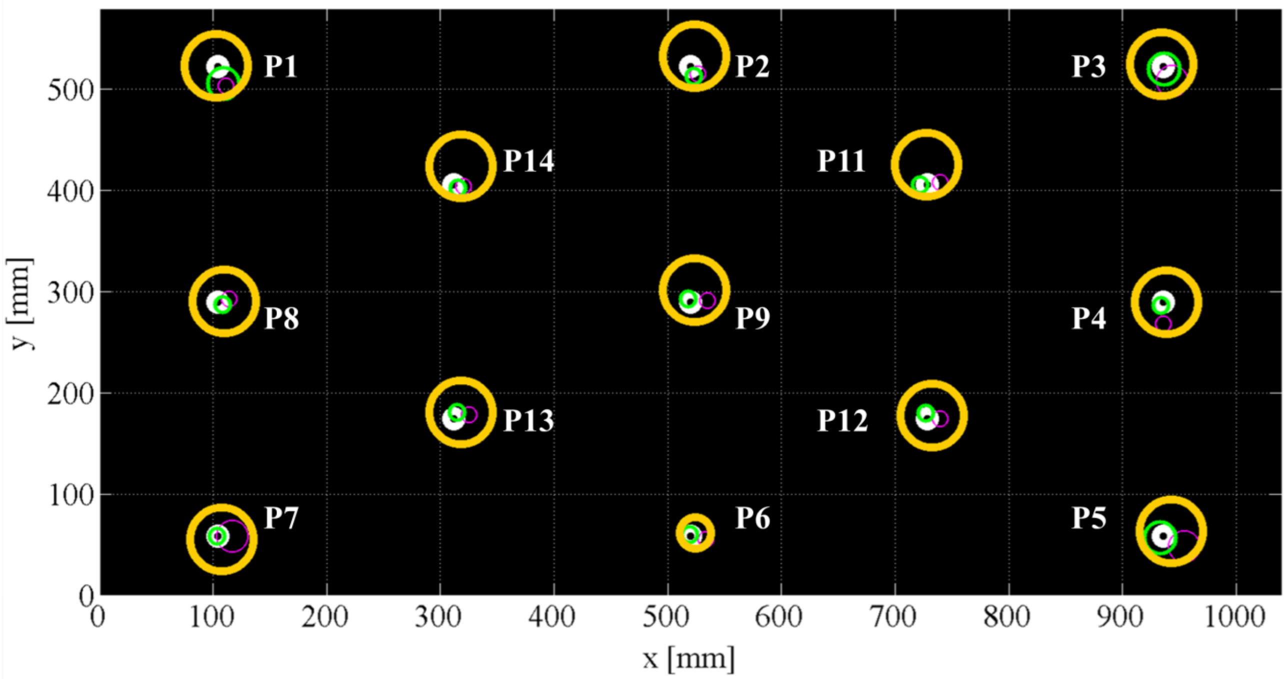

Fig. 4. A representation of the PoG data on the dot target locations (black dots) for st550 (thin magenta), st650 (green) and st750 (thick yellow). The circle size is representative of the dispersion around the mean value (circle center) of the PoG: sd<3 mm small radius circle, 3 mm <sd<6 mm medium radius circle and sd>6 mm large radius circle.

(Tobii Studio) [13]. During the calibration, participants were asked to look at a dot target appearing at nine different locations on the screen. The results provided by the calibration were consistent with the level of precision and accuracy provided by the manufacturer [12]. The eyes position was calibrated with respect to the headband markers, by placing two retro-reflective markers on the eyelids during an *ad hoc* preliminary acquisition. The eyes midpoint position was then computed and used to determine the distance between the subject and the ET.

To assess the maximum linear and angular ranges of motion of the head within which the gaze can be measured (volume of trackability), different types of head motions were recorded. In particular, each subject was asked to look at a dot target located in center of the screen, while moving the head along the AP (*tAP*, ±200 mm), the ML (*tML*, ±100 mm) and the V (*tV*, ±100 mm) directions and rotating the head around the ML (*rML*, ±50 deg) and the V (*rV*, ±50 deg) directions.

To determine the influence of the stimulus location and the effect of the distance from the ET, the subjects were asked to look at a dot target displayed sequentially in 13 different locations on the screen. The dot persisted in each location for two seconds. The first nine positions coincided with those of the calibration grid (P1:P9). The four remaining positions (P10:P13) were located as shown in Fig. 2. Recordings were performed with the participants standing at 550 mm (*st550*), 650 mm (*st650*) and 750 mm (*st750*) from the ET.

To test the ET performance during gait, the subjects were asked to look at the 13 dot-grid while walking at two different speeds (*walk1*: 0.6 m/s and *walk2*: 1.1 m/s).

To evaluate the feasibility of the adopted VR-based experimental set-up for the analysis of gaze, the number of gaze fixations, falling in a rectangular object (120×60 mm^2), was quantifed. The rectangular object was first kept still at the center of the screen for 10 s. Then, it was made moving horizontally at 85 px/s). The subjects were asked to look both at the static and dynamic rectangles while standing (*st_stand; dyn_stand)* and while walking at 0.6 m/s (*st_walk; dyn_walk*).

For all recordings, the ET and the stereo-photogrammetric systems were synchronized. Participants rested between each task acquisition.

B. Data Processing

For each sample, the x- and y-coordinates of the PoG were measured. Blink artifacts, short gaze deviations, undesired eyes movements and flickering were removed from the PoG data [10], [14].

For each acquisition, head position and orientation were computed. For each subject, the volume of trackability was estimated and the lowest common volume was determined over the subjects (*VoT*).

For each dot target location and subject, bias and standard deviation of the measured *PoG* were computed (*b*, *sd*). For every i^{th} dot target, the latter values were averaged over the subjects ($\overline{b_i}$, $\overline{sd_i}$). $\overline{b_i}$ and $\overline{sd_i}$ were averaged over the 13 dots of the grid obtaining $\overline{b}$ and the relevant standard deviation ($\overline{sd}$). The maximum and minimum

values of $\overline{b_\iota}$ and $\overline{sd_\iota}$ were also computed over the 13 dots of the grid (max($\overline{b_\iota}$), max($\overline{sd_\iota}$), min($\overline{b_\iota}$) and min($\overline{sd_\iota}$)).
Gaze fixations were computed by applying a velocity-based classification algorithm (I-VT filter [15]) to the gaze measurements. The velocity threshold was chosen equal to 30 deg/s [16]. To estimate the gaze fixations hitting the surrounding of the rectangular object, an AoI was defined around it. The AoI size was determined adding a margin equal to *walk*2 max($\overline{sd_\iota}$) to the object size [10]. The AoIs were analyzed using the Tobii Studio. The percentage of gaze fixation hitting the AoI, with respect to the total number of gaze fixations occurring during the stimulus presentation time, was computed and averaged over the subjects (*Fix%*).

III. RESULTS

A description of the volume of trackability obtained for each subject and the *VoT* during *tAP*, *tML*, *tV*, *rML* and *rV* are provided in Fig. 3.
The values found for max($\overline{b_\iota}$), max($\overline{sd_\iota}$), min($\overline{b_\iota}$), min($\overline{sd_\iota}$), $\bar{b}$ and $\overline{sd}$ for tasks *st550*, *st650* and *st750* are reported in Table 1.
For tasks *walk1* and *walk2*, max($\overline{b_\iota}$), max($\overline{sd_\iota}$), min($\overline{b_\iota}$), min($\overline{sd_\iota}$), $\bar{b}$ and $\overline{sd}$ are reported in Table 2.
For tasks *st550*, *st650* and *st750*, $\overline{b_\iota}$ and $\overline{sd_\iota}$ values are depicted in Fig. 4.

Table 1. Average, minimum and maximum values of $\overline{b_\iota}$ and $\overline{sd_\iota}$ for tasks st550, st650 and st750.

[mm]	*st550*[a]	*st650*	*st750*
$\bar{b}$±$\overline{sd}$	17±3	11±3	18±7
max($\overline{b_\iota}$)± max($\overline{sd_\iota}$)	26±5	17±5	30±9
min($\overline{b_\iota}$)± min($\overline{sd_\iota}$)	13±2	6±3	10±5

[a] In task *st550*, gaze data was lost for most of the dot target locations for two subjects. Parameters are computed excluding these locations.

Table 2. The average, minimum and maximum values of $\overline{b_\iota}$ and $\overline{sd_\iota}$ for tasks walk1 and walk2.

[mm]	*walk1*	*walk2*
$\bar{b}$±$\overline{sd}$	11±4	12±5
max($\overline{b_\iota}$)± max($\overline{sd_\iota}$)	17±6	17±14
min($\overline{b_\iota}$)± min($\overline{sd_\iota}$)	7±4	8±4

Table 3. The percentage of fixations hitting the rectangular objects in tasks st_stand, dyn_stand, st_walk and dyn_walk.

Task	*Fix%* [%]
st_stand	93±9
dyn_stand	87±11
st_walk	98±3
dyn_walk	85±18

During tasks *walk1* and *walk2,* for each subject, the head position and orientation was always within its corresponding volume of trackability. Despite this, PoG data were lost in one subject for those dot targets located in the bottom half of the screen (P4-P8, P12 and P13). In Table 3, the percentage of gaze fixations is reported for the analyzed conditions.

IV. DISCUSSION

The present study was carried out to verify if a remote ET could be used to analyze the gaze of subjects walking on a treadmill while looking at different locations on the screen.
To this purpose, a preliminary analysis of the inaccuracy factors, expected to influence the ET performance, was carried out.
Given the specific experimental set-up employed in this study, the linear range of trackability along the ML direction was similar to that provided by the manufacturer (±100 mm), while smaller ranges of trackability along the AP and V directions were found (AP: -30 / +80 mm *vs.* ±150 mm; V: -73 / +61 mm *vs.* ±100 mm). No reference values are provided by the manufacturer for the angular ranges of trackability.
Results showed that the distance between the subject and the ET is a critical factor, since it influences both the percentage of lost data and the accuracy and precision of the estimated PoG. As expected, the best results were achieved, consistently to the manufacturer specifications, at a distance of 650 mm from the ET ($\bar{b}$±$\overline{sd}$=11±3 mm). Conversely, accuracy and precision worsened as the eyes moved from the optimal distance and some data loss occurred at 550 mm.
The stimulus location did not influence accuracy and precision of the PoG measurements in any of the analyzed distances.
In general, during walking, PoG data was robustly estimated with high values of accuracy and precision.
For the tallest subject analyzed (1.87 m), some gaze data loss occurred during the slow walking, probably due to a non-optimal screen height which was the same for all subjects. The walking speed did not influence the measurements accuracy and precision.
The percentage of fixations hitting the static and dynamic rectangles were always higher than 85%, both during standing and walking. Fixation percentages were higher when the rectangle was static compared to when it was moving (>93%). This is probably related to the eyes small smooth movements while following the slowly moving object (*smooth pursuit*) and the I-VT filter included in the Tobii studio software is not specifically designed for the analysis of such eye movements [15]. *Ad hoc* algorithms for the analysis of gaze when following slow moving objects need to be devised. The high fixation percentage during walking suggests that the proposed experimental set-up may be used for tracking gaze while

watching VR objects during gait.

In summary, the preliminary outcomes of this study may provide insights for the design and implementation of analytical and experimental procedures for the combined analysis of gaze and human locomotion in VR-based applications. Possible applications of the proposed experimental set-up include rehabilitation programs for people at high risk of fall to improve their gait strategies in their daily life.

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