Redirected Walking within a VR Exergame for Return-to-Sports Screening

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***Abstract*—Sports rehabilitation exercises and return-to-sports screening are typically conducted in confined spaces that lack the highly motivating environments found in stadiums filled with people. Virtual Reality (VR) can be employed to virtually recreate those settings. A challenge in VR sports is that running exercises with six degrees of freedom can pose a risk due to potential collisions with obstacles. Redirected walking addresses this issue by utilizing techniques that adjust the user's virtual motion in relation to their physical motion. This study evaluates the established positive perceptual bounds of redirected walking and extends its application to a reaction-based exercise. In this proposed use case, the user must chase the ball from one point to another in the room. Our findings indicate that rotational manipulations impact user experience at +44% rotation, which is stricter than the established +49% rotation bound. For translational manipulations, our research shows that the established +26% translational bound can be extended to +41% without a significant difference in self-reported subjective experience. This study demonstrates that redirected walking manipulations do not lead to significant changes in participants' total reaction times. In conclusion, the findings of this study illustrate that redirected walking techniques, with careful consideration of the bounds on rotational and translational manipulations, can be effectively applied in a Virtual Reality exergame designed for return-to-sports screening. This offers a more engaging alternative to traditional rehabilitation environments.**

***Index Terms*—redirected walking, virtual reality, exergame**

I. Introduction

In current rehabilitation programs, motion analysis is employed to provide physical therapists with a better understanding of how athletes recover from injuries. This motion analysis is often carried out in a small, enclosed room using camera equipment. The athletes are then required to perform a series of exercises in that room. Ideally, the athlete should exert maximum effort during exercises. Only then can physiotherapists obtain the most reliable data on the user's recovery from injury.

This study integrates Virtual Reality (VR) into common soccer exercises and examines how VR can help in achieving this goal. Such integration of exercises and game is called an exergame [1]–[3]. Through VR, users are completely immersed in a virtual environment and lose awareness of their real surroundings.

Without a sense of the physical environment (including its boundaries), it can be dangerous to perform VR exercises that require users to move within the room. As a solution, redirected walking [4] applies (subtle) differences between the mapping of the physical world to the virtual world. As such, large virtual environments can be mapped onto smaller physical spaces, and users can be directed away from obstacles. However, there is a limit to how strong these manipulations can be without negatively affecting the user's experience. Our proposed experiment examines how established upper bounds [5] on redirected walking manipulations apply to a sports situation. In particular, manipulations in the user's virtual translation and rotation are examined during a reaction speed exercise where the user must chase the ball from point to point.

This paper is organised as follows. First, Section II discusses related work. Then, proposed experiment is described in Section III, and its conditions are subsequently listed in Section IV. Afterwards, the results are discussed in Section V. Finally, the paper is concluded in Section VII.

II. State of the Art

When VR experiences are conducted with 6 degrees of freedom, there is a danger of users colliding with obstacles in the real environment. Redirected walking [4] tries to resolve this issue by applying manipulations in the user's virtual motion. These manipulations are defined in terms of gains, i.e., added or removed fractions of virtual motion compared to the user's physical motion [6], [7]. The most common types of gains are rotational, translational and curvature gains. Rotational gains scale the user's virtual rotations relative to the user's physical rotations. Similarly, translational gains scale the user's virtual translation relative to the user's physical, real translation. Curvature gains add a constant amount of rotation such that the user must physically walk along a circle to keep walking along a straight line in the virtual environment.

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There are limits to how big these manipulations can be without being noticeable to the user. The thresholds of Steinicke et al. [5] are still commonly used [6]. They concluded that rotations can be downscaled by 20% and upscaled by 49% for virtual rotations of 90°. However, Bruder et al. [8] suggest that these bounds are lower when the virtual rotations are larger than 90°. Translations can be downscaled by 14% and upscaled by 26%. Also note that users unconsciously compensate for translational gains with a reduced walking speed [9]. This means that applying positive gains provides the appearance of walking faster virtually but slows down the user in the real world in order to negate the fast movement. For curvature gains, a circle radius of 22 meter (m) was established as threshold for both curvature to the left and right. Here, Neth et al. [10] argue that curvature is more noticeable if users walk faster.

The alignment-based redirection controller (ARC) [11] guides the user in a manner that aligns their distance from obstacles in the real environment with their distance from virtual obstacles, aiming for maximum similarity between the two. Other work [12] proposes a a mapping algorithm utilizing Bezier curves to dynamically distort virtual space and implement multiperspective fusion to enhance visualization. In the work of Strauss et al. [13], reinforcement learning (RL) was used to train a deep neural network, which was tasked with directly determining the rotation, translation, and curvature adjustments needed to modify a virtual environment based on the user's position and orientation within the tracked space.

Since all the work in the state of the art is focused on slow paced use cases, the proposed work wants to validate whether the bounds of the state of the art can be translated to the challenging scenario of a Virtual Reality exergame designed for return-to-sports screening.

III. Proposed Experiment: Redirected El Rondo

Our proposed experiment aims to evaluate rotational and translational gains on a reaction speed exercise called *El Rondo*, in relation to the established results of Steinicke et al. [5]. Note that we limit the scope by not exploring curvature gains, because these gains do not fit the *El Rondo* exergame use case and seemed more dangerous to perform in a fast paced exergame.

The virtual environment of this experiment depicts an *El Rondo* soccer exercise as shown in Fig. 1. In this exercise, the user is standing inside a circle of Non-Playable Characters (NPCs). By default, this circle has a radius of 2.5 m. The odd numbered NPCs are placed more outwards to give the user more running space.

Experiments on subjects are performed in multiple trails, with each trail containing 20 pass iterations. During one pass iteration of the exercise, one of the NPCs has the ball and passes it to a random player positioned opposite to the NPC. The user must then chase the ball from NPC to NPC. In order to reduce the variability of how close test subjects come to the NPCs, a red, spherical marker is placed 1 m in front of the NPC that receives the ball. When the user first stands above this marker, it turns green and registers the time between the pass of the previous NPC and the arrival of the user at the marker.

Fig. 1: In-game image of the virtual environment during the El Rondo scenario. The user runs within the circle of NPCs.

Multiple pass iterations are combined into a trial. In particular, 20 pass iterations are executed with 10 having redirected walking manipulations turned on. These frequencies are inspired by the experiment design of Steinicke et al. [5]. The order is randomized for each trial and person. Pass iterations follow each other after 2.5 seconds. This time interval forces the user to react quickly, while also ensuring that there is some spare time before the start of the next iteration, preventing user exhaustion.

Only positive gain values are used in the trials because negative values could not be used safely in the 9x9 m² room. Negative translation gains make the virtual environment bigger than the real environment. Negative rotation gains may not rotate users far enough when they are facing a wall.

When redirected walking is active, positions of the virtual NPCs in the physical world dynamically change while the user is moving. This can result in some NPCs being located outside of the room's safety bounds. As it is not initially known if an NPC will be inside the safe zone at the end of the passing iteration, our application predicts where the user ends up when they move to a candidate NPC to pass to. Any candidate NPCs with a predicted physical motion vector that extends beyond the safe area are eliminated from consideration. If there are no candidates, the pass iteration is skipped. For redirected walking with rotation gains, the NPC circle was consequentially shrunk to a radius of 2 m because iteration skips were too frequent with the 2.5 m radius.

For translation gains, the prediction assumes that the user walks in a straight line towards the next NPC. This assumed virtual motion vector is then scaled with the redirection gain to obtain a predicted physical motion vector. For rotation gains, the prediction assumes that the user first rotates along the smallest angle towards the next NPC and then moves along a straight line towards that NPC. Similar to the translational case, the effect of the gain is calculated on the assumed virtual motion vector to obtain a physical motion vector.

The used translational gains are given by $g_T = \{0.21, \mathbf{0.26}, 0.31, 0.36, 0.41\}$, and the rotational gains are given by $g_R = \{0.44, \mathbf{0.49}, 0.54, 0.59, 0.64\}$, in which the bold value is the threshold established by Azmandian et al. [14]. We include one sample below the threshold and 3 samples above the threshold, based on the hypothesis that the higher gains would be less noticeable during a more intense sports activity. Each gain is used during one trial. The order of trials is randomized for each participant. However, the first trial does not use any redirected walking and is used to set a reference for all other trials.

After each trial, participants had to fill in a Slater-Usoh-Steed (SUS) [15] presence questionnaire, an Intrinsic Motivation Inventory (IMI) [16] questionnaire, and a custom questionnaire. The IMI questionnaire consisted only of the interest/enjoyment and pressure/tension subscales. The custom questionnaire consisted of the following 5 questions:

1) How often did you lose balance?
2) How often did you feel disoriented in terms of distances and turning angles? Think of how many times you misjudged how much you had to run or how much you had to turn.
3) Did the distances and turning angles in the virtual environment ever feel smaller or larger than those in the real world?
4) How often did you feel like you overestimated or underestimated your running speed?
5) How often did you feel like you overestimated or underestimated your turning speed?

Answers were given on a scale of 1 to 7 where 1 represents *at no time* and 7 represents *almost all the time*. Scores on the custom questions are summed to obtain a total noticeability and hindrance score due to redirected walking. A higher score represents more noticeable and annoying manipulations. The interval times between a pass and arriving at the next marker are summed up for each trial to obtain the task completion time measure.

IV. Experiment Conditions

We recruited 18 people to participate in the experiments. Participants' ages ranged from 19 to 27 years ($M = 22.8$, $SD = 1.9$) with 6 persons who identified as female and 12 participants who identified as male. Additionally, participants had to answer which sports they had practiced in an organized way for more than a year. Soccer was the most popular sport, with 7 people who had played soccer for more than one year.

Experiments were carried out in an 9x9 m² room. For the experiments, only a 7x7 m² area was used to have a safety margin. When participants left the safe area, they received a textual warning on the Head Mounted Display (HMD) and heard a loud whistling noise. The Oculus Quest 2 was used as HMD because of its light form factor for sports exercises.

Results were analyzed using analysis of variance (ANOVA) when its assumptions were satisfied. When one of the ANOVA assumptions was not satisfied, non-parametric Kruskal-Wallis tests were used.

TABLE I: ANOVA results for the IMI scores on the interest/enjoyment and pressure/tension subscales for different gain types.

Gain Type	Subscale	F	p
translational	interest/enjoyment	1.533	0.188
translational	pressure/tension	0.720	0.610
rotational	intereset/enjoyment	1.801	0.122
rotational	pressure/tension	0.538	0.747

V. Results

Skip iterations occurred in 18 out of the 180 trial results. All these trials were filtered out for the task completion times, as skips resulted in unrepresentative low times. Only trials which included more than 2 iteration skips were removed from the questionnaire answers. This resulted in two deleted trials.

One participant's results for both the task completion times and questionnaires were removed during analysis. All other participants stayed at the marker position until the next iteration started, but this participant always returned to the center of the circle before the next iteration started. This resulted in their self-reported noticeability and task completion times being outliers on the lower end.

For the translational gains' results, a non-parametric Kruskall-Wallis test was conducted, as ANOVA's normality assumption was not satisfied. The test did not reveal significant differences in task completion times for different translational gains ($\chi^2 = 2.046$, $p = .843$). For the rotational gains' results, a one-way ANOVA also did not show significant differences in task completion times for the different rotational gains ($F = 0.900$, $p = .469$).

In order to account for variations in individual capabilities, the task completion time of each person in the reference trial was subtracted from their task completion times in other trials. A one-way ANOVA did not reveal significant differences in centered task completion times for translational ($F = 0.424$, $p = .791$) or rotational gains ($F = 1.224$, $p = .309$).

SUS scores were calculated by counting all answers higher than 5. Here, a non-parametric Kruskal-Wallis test was executed because ANOVA's normality assumption was not satisfied. The Kruskal-Wallis test did not reveal any significant differences in SUS scores for both the rotational ($\chi^2 = 7.817$, $p = .167$) and translational ($\chi^2 = 2.369$, $p = .796$) cases.

IMI scores were calculated for the pressure/tension and interest/enjoyment subscales. A one-way ANOVA did not reveal significant differences in IMI scores in all cases, as can be seen in Table I.

The set of custom questions had a Cronbach's Alpha of $\alpha = 0.8491$, which indicates that all questions consistently evaluated the same concept. The answers to each question grouped by gain type can be seen in Fig. 2.

The participants' total scores can be seen in Fig. 3 and Fig. 4. A one-way ANOVA found significant differences in the scores for both rotational ($p < 0.05$) and translational ($p <$

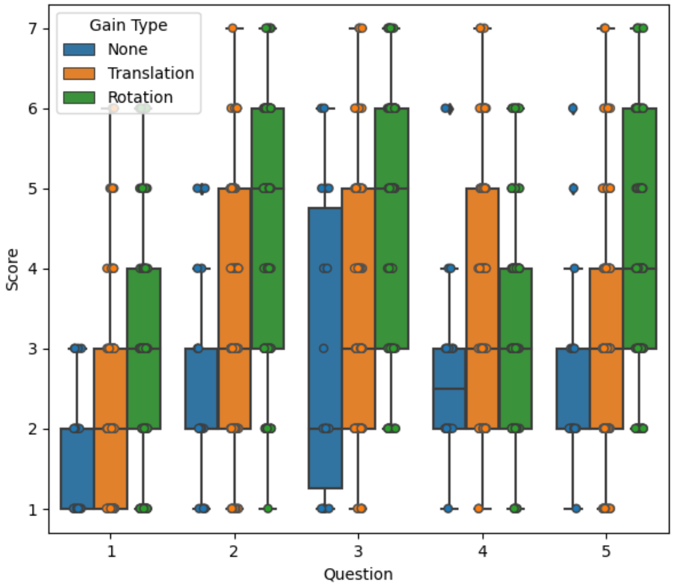

Fig. 2: Boxplot of the answers to each custom question, grouped by applied gain type.

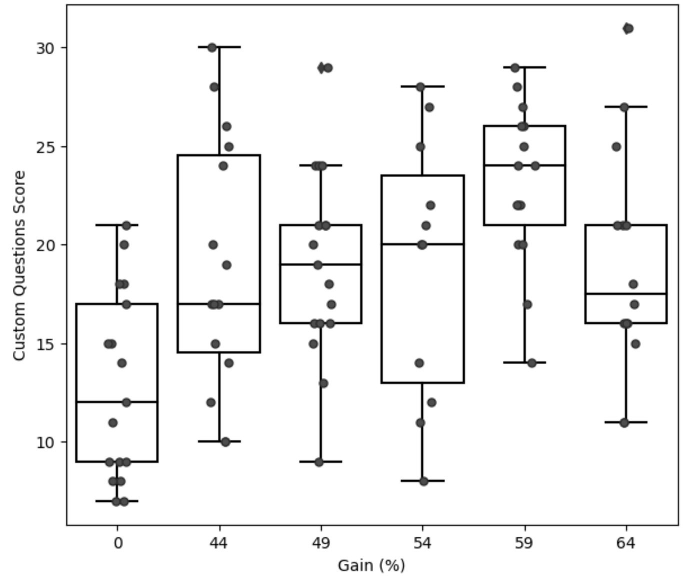

Fig. 4: Boxplots of the custom questionnaire scores for different rotational gains.

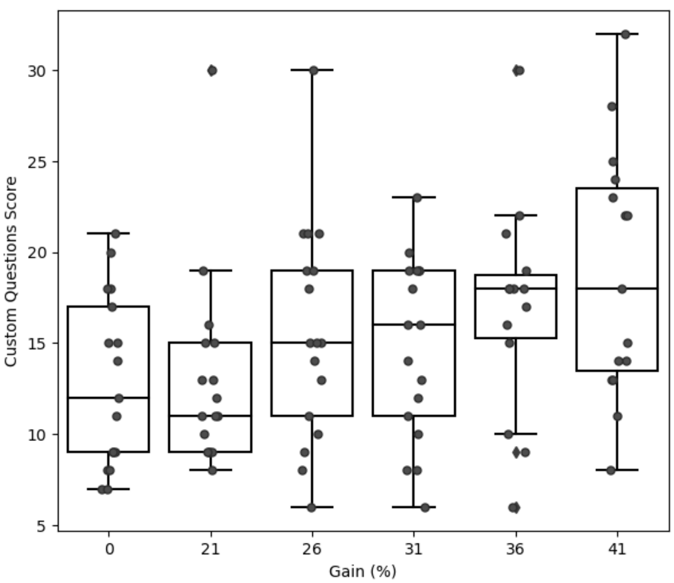

Fig. 3: Boxplots of the custom questionnaire scores for different translational gains.

0.05) gains. For rotational gains, a post-hoc Tukey-Kramer test showed significant increases ($p < 0.05$) in score compared to the reference trial for rotational gains of 44%, 49%, 59%, and 64%. For translational gains, a post-hoc Tukey-Kramer test showed significant increases ($p < 0.05$) in score for the couples (0%, 41%) and (21%, 41%).

VI. Discussion

No statistically significant differences were found in the (centered) task completion times for different rotational and translational gains. This suggests that the persons' total reaction times are not significantly different using temporarily heavy-gain applications. This can support the use of gain values above perceptual bounds in similar high-reaction-speed exercises.

Only the custom question scores were able to show significant changes in the subjective experience of the user. All non-zero rotational gains except one resulted in significant differences with the reference trial. This indicates that users may be more sensible to rotational manipulations during this type of exercise. For translational gains, only the most extreme gain (+41%) showed a significant score increase over the reference case and the lightest redirected walking case (+21%). This indicates that users may be less sensible to translation gains during more intense sports situations.

Together, these results suggest that translational manipulations can be pushed above the thresholds of Steinicke et al. [5] without causing significant differences in both subjective experience and objective experience in high-reaction-speed exercises. For rotational gains, the opposite holds in respect to the subjective experience. That is, gains below the thresholds of Steinicke et al. [5] may be required to keep subjective experience unchanged.

That both IMI and SUS questionnaires showed no significant changes may indicate that these measurements were not ideal for this use case. A standardized questionnaire for redirected walking experiments could be a valuable addition for self-reported redirected walking noticeability in future research.

The study evaluates the impact of redirected walking techniques on a specific reaction-based exercise involving chasing a ball. However, it's essential to assess the generalizability of these findings across a broader range of sports-related activities and exercises commonly used in rehabilitation programs. Different exercises may pose unique challenges and require different levels of precision and interaction within the virtual environment.

While VR offers the potential to recreate highly motivating environments, the level of realism and immersion provided by current VR technology may still be limited. Future developments in VR hardware and software should focus on enhancing realism, such as incorporating more realistic physics simulations, haptic feedback, and improved graphics to better mimic the experience of being in a stadium or engaging in sports activities.

The paper acknowledges the risk of collisions with obstacles during running exercises in VR with six degrees of freedom. While redirected walking techniques mitigate this risk to some extent, there is still a need for robust safety measures to prevent accidents or injuries, especially in rehabilitation settings where users may have physical limitations or impairments.

VII. Conclusion

This work introduces redirected walking into a reaction speed exercise. Participants had to chase a ball from point to point while their virtual motion was manipulated. In particular, physical rotations and translations were amplified in the virtual environment.

Redirected walking manipulations did not result in significant changes in the participants' total reaction times. This suggests that for this type of activity, temporary use of large gain values does not drastically affect the total performance.

Significant differences were found for a custom questionnaire evaluating redirected walking noticeability and hindrance. The total scores of this questionnaire showed significant increases for all rotational gains except one and suggest that values below the +49% threshold can have an impact on the user's subjective experience in this context. For translational gains, only significant differences were found for the largest gain value (+41%). This suggests that there is more freedom here in choosing an upper bound around the established +26% threshold.

In conclusion, the findings of this study illustrate that redirected walking techniques, with careful consideration of the bounds on rotational and translational manipulations, can be effectively applied in a Virtual Reality exergame designed for return-to-sports screening. This offers a more engaging alternative to traditional rehabilitation environments.

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