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Estimation of Body Sway Dynamics in a Soft Actuators-based Exercise Game with Squat Motions

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Abstract— **Postural stability is a significant aspect that needs to be investigated to prevent the risk of injuries and falls in all age groups. Moreover, developing reliable techniques and feedback modalities to enhance the posture control evaluation is crucial. The study investigates the effects of incorporating self-simulated gaming exercises with haptic feedback on posture control in young adults. Participants were randomly assigned to three groups: a control group (n=10) which performed conventional squatting within prescribed time intervals; an intervention group A (n=9), which engaged in virtual reality (VR)-based squatting; and an intervention group B (n=9), which performed squatting in a VR environment while wearing a soft actuator suit. The gaming interface dynamically optimizes the difficulty of squatting based on the user's knee tremor. We evaluated several center of pressure (COP) parameters: displacement, root mean square (RMS), area, median frequency, and mean velocity in the mediolateral (ML) and anterior-posterior (AP) directions. Statistical analysis using ANOVA revealed significant effects in the ML displacement between the control group and intervention group B (p = 0.027), ML RMS between the control group and intervention group A (p = 0.001), and between the control group and intervention group B (p = 0.001). Additionally, significant differences were observed in the circumference area between the control group and intervention group A (p = 0.035) and between the control group and intervention group B (p = 0.001). The findings indicate that the developed prototype, which provides visual and haptic guidance, shows promise as a tool for improving postural control.**

Index Terms— **Exergames, soft actuators, squatting, postural variations, human augmentation**

I. INTRODUCTION

Physical exercises are primary methods of enhancing physical health through comprehensive engagement in various physical activities. Physical exercises are pivotal in sports and rehabilitation, enhancing athlete performance, flexibility, and strength while managing pain and promoting proper mobility. The stability of the individual is heavily reliant on the proper functioning of neurological and locomotive systems. Dynamic postural control is crucial in many sports as it involves various motions such as cutting, landings, etc. There has been an increasing focus on understanding the body's capacity to maintain equilibrium, driving continuous advancements in the methods and approaches employed for quantitative assessment. Young adults are frequently vulnerable to daily life injuries and serious accidents, which might lead to musculoskeletal damage. For athletes and fitness-oriented individuals, exercise injuries are increasing for various reasons, such as a lack of proper technique and inadequate knowledge of posture control during exercise training. It is essential to regulate posture to maintain stability for all age groups and improve daily life activities (ADL). It is strongly recommended to engage in training programs, as they contribute to enhanced balance function and improve physical health through various measures [1]. Researchers and experts are involved in proposing effective feedback modalities to achieve better stability and posture regulation, preventing higher injury risks such as anterior cruciate ligament (ACL) ruptures or ankle ligament injuries during muscle training or improper postures. The primary feedback types include visual feedback with VR and haptic feedback with soft actuator augmentation. There are various steps to maintain the posture, which leads to an improved balance for human motion [2], [3].

In this research, we aim to investigate the effects of using a force feedback-based system to identify the body sway characteristics that involve squatting in terms of traditional training, VR-based training, and VR-combined actuators-based training in a randomized manner as shown in Fig. 1. We discuss the various research utilizing VR and haptics-based modules for effective posture training and their hypothesis in section 2. We have explained the characteristics of soft actuators, exergame components, user sessions, and participants in section 3. We include the experiment protocol and data collection process in section 4. We describe the results and discuss the correlations and further improvements for this study in sections 5 and 6. Finally, we conclude the paper in the last section.

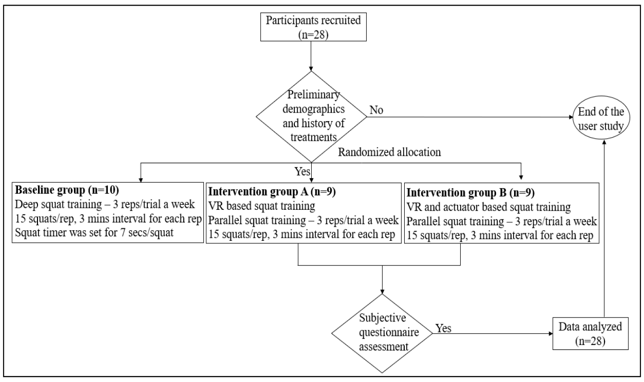

Fig. 1. Experimental flow chart for conventional and VR-based squat training to evaluate postural changes

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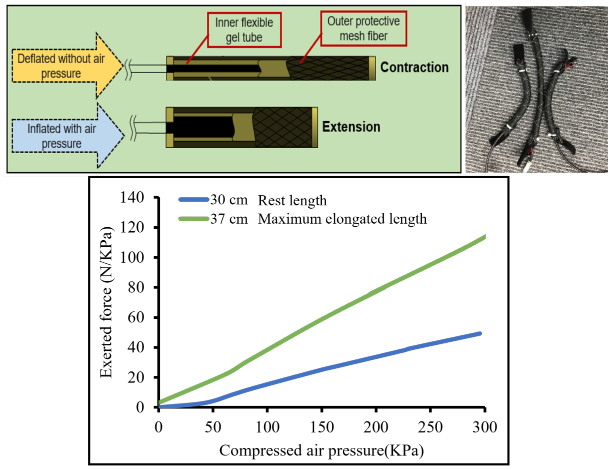

Fig. 2. A schematic representation of PGM and force-pressure characteristics with rest length of 30cm to stretched length of 37cm actuators.

II. RELATED WORKS

Virtual reality (VR) is an increasingly used tool in sports science through fitness models and the medical field through rehab techniques. The study [4] investigated the effectiveness of posture preservation during gait in chronic stroke patients. An influential approach [5] using virtual representations of unsupervised exercises has shown positive functional training effects in enhancing lower limb motions for spinal cord injury (SCI) patients. Visual feedback via VR in correcting postures enhances awareness, precision, and engagement [6]. This immersive technology provides real-time visual cues, allowing individuals to immediately adjust their posture, promoting better alignment and overall postural improvement [7].

Incorporating games that combine exercise opens up a pathway to amplify the efficacy and involvement in exercises to improve posture [8]. With the development of exergames, it is easy for common individuals, including the elderly targets, to adapt and accept at-home physical training and rehabilitation technologies to increase physical and mental health [9]. Providing instant visual feedback through these exergames suggests the users correct their postures during exercise performance, which prevents knee and other injuries in the lower extremities [10]. The effectiveness and precision can be further improved by integrating augmented reality through pneumatic actuators, providing real-time outcomes with visual and haptic feedback [11]. We have introduced squats, one of the most common exercises to enhance overall body strengthening and conditioning, particularly targeting the lower extremity if performed correctly [12].

III. METHODOLOGY

A. Soft actuators- Pneumatic Gel Muscle (PGM)

A pneumatic actuator designed for operation within a compressed air range of 0.05 MPa to 0.3 MPa features an internal structure comprising a flexible soft tube made of a specific styrene-based thermoplastic elastomer. This inner tube is externally shielded by a plastic mesh for added flexibility and protection. In contrast to the conventional McKibben pneumatic artificial muscle (PAM), which requires higher air pressure for increased force, the PGM's soft inner tube demands a lower volume of air pressure within the specified range. This characteristic makes it more appropriate for developing augmented motion suits due to its flexibility and soft composition. When appropriately attached to corresponding joint counterparts, the PGM can supply a specific quantity of torque to both sides of the lower extremity joints. Fig. 2 illustrates the characteristics of force-to-pressure changes for the maximum stretched length of 37 cm to the rest length of 30cm, as modeled in our previous work [13].

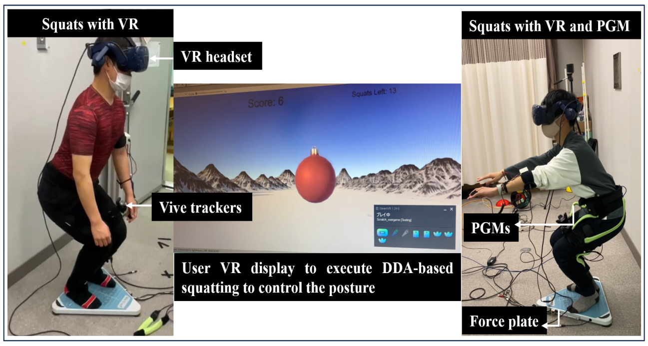

Fig. 3. Dynamically adjusted difficulty conditions for two intervention groups where the user performs squatting with changes in the movement speed during squats with VR session and changes in the movement speed and assistive force exerted to provide required support during the squats with VR and PGM session.

B. Exergame instrumentation

The development of the exergame design utilized the HTC Vive virtual reality module, and simulation capabilities were facilitated through UNITY, creating an enriched VR space for a fully immersive experience. We used the head mount display (HMD) and the trackers at the knees and torso to define the squatting position based on the user's ability. They were also used to track the motions of the lower extremity. We used the user's height and position of the trackers for calibration. The four different squat phases defined for setting up the squat depth threshold in UNITY were idle, onset, during squat, and end. Detailed descriptions of these phases can be found in the earlier study of [14].

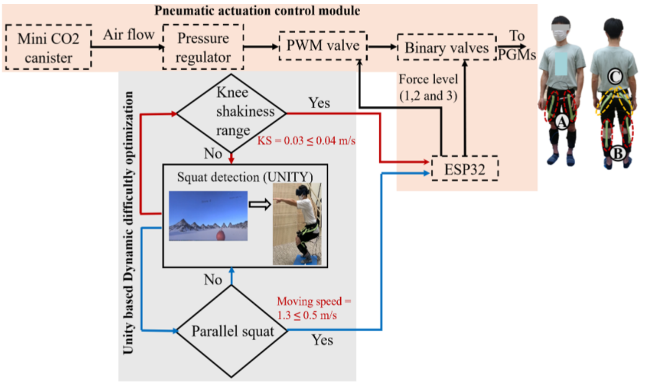

Fig. 4. Control unit for soft actuators integrated with UNITY platform to enable DDA optimization

TABLE I

SUBJECT ANTHROPOMETRIC FEATURES

Group	N	Gender (male/female)	Age (years)	Height (cm)	Weight (kg)
Baseline	10	8/2	19.9(0.9)	169.3(6.9)	57.8(6.7)
VR	9	7/2	20.3(0.7)	170.2(7.7)	61.7(10.3)
VR and PGM	9	7/2	20.3(0.8)	169.3(9.2)	59.5(10)

The first gaming conditions include squatting while collecting the object on the path in the VR space depending on the difficulty level set with the movement speed of the object, which is optimized in the range of $1.3 \leq 0.5$ m/s. The second condition includes the same training, varying the movement speed and level of force for assistance ($60.17 \geq 75.34$ N for hip flexion and $25.01 \geq 32.45$ N for knee flexion) by PGMs. At the same time, the resistance of $90.51N$ is constantly provided with soft actuators to restrict the deep squat motion. Knee shakiness ($0.02 \geq 0.04$ m/s) exerted by the user will decide the difficulty condition by setting up the threshold for the movement speed and air pressure for soft actuators. Fig. 4 represents the PGM actuation control system based on the difficulty conditions applied.

C. Participants

Twenty-eight young adults participated in the user study. Anthropometric measurements were taken and indicated in Table I. The users were informed prior about the randomized tasks with VR and VR combined actuators-based squat training. As squatting is an intensive motion to enhance the lower limbs, the participants were requested not to be involved in severe physical workouts until the end of the user study. We informed the subjects to engage in pretrial sessions to become familiar with VR and soft actuator-based augmented training. We confirmed no discomfort and VR simulation sickness before the study. The research ethics committee of the Institutional Review Board (C-342) under Hiroshima University has approved the study. It was conducted according to the ethical standards included in the Declaration of Helsinki. All users were undergraduate students who signed an informed consent form before participation.

D. User sessions

The user study comprises three sessions: conventional squat training, VR-based squats, and VR-based squats augmented with soft actuators.

In session 1, the subjects perform squats within the specified time and counts indicated on the phone app. We have fixed the squat counts of 15 per rep (repetition), which accounts for 45 squats for three reps per week. During this traditional training, each squat takes approximately 7 seconds.

In session 2, the users perform squats in a VR space created by HTC VIVE and the Unity module. This training also accounts for the same squat counts as session 1, but the time varies depending on the task for performing parallel squats. In this session, the user must collect the items visible on the moving path in the ski area, which makes the user perform parallel squats while maintaining the posture as shown in Fig. 3 (squats with VR). The game difficulty was adjusted using the movement speed of the game objects depending on the knee shakiness exerted by the user [14].

In session 3, the user performs parallel squats as in session 2. The game difficulty was adjusted using the movement speed and the air pressure exerted to provide assistance and resistance with PGMs. We used six sets of PGMs, four of which were affixed to assist knee and hip flexion as shown in Fig. 3 (squats with VR and PGM). The remaining two sets were attached to resist the hip extension motion throughout sessions 2 and 3. The studies [15], [14] represent the schematic representation of the control algorithm for the PGM actuation.

IV. DATA ANALYSIS

A. Postural sway measurements

A portable gravicorder (BW-6000+MD, ANIMA, Tokyo) was used to evaluate the projection area of the center of gravity, which in turn measures kinetic changes at the center of pressure required to measure the changes in the body sway during squatting. The sampling frequency is 50Hz. The users were asked to stand on the gravicorder while attaching exergame components and PGMs corresponding to the user sessions. For conventional squatting, the user performs the deep squats within the specified time while standing on the force plate. In sessions 2 and 3, the user will squat when the gaming VR scene is played. The user will perform two trial squats for the calibration to record the user's height to set the moving object's height from the ground. The two trial squats will adjust the user dimensions only after the calibration. This will sync the squatting movement of the user according to the objects reachable to collect by colliding with the HMD. The synchronization was also done according to the moving speed with the varying knee shakiness in session 2 and the moving speed and level of resistance and assistance applied with PGMs with the varying knee shakiness in session 3. It is also possible for the users to see the final scores, squat counts, and PGM modes of assistance, such as ON or OFF, during gameplay.

B. Data collection and data process

The study involved acquiring three components of momentum and force values (anterior-posterior - AP, medial-lateral - ML, and vertical). Following the calculation of signal means, we excluded posterior data for subsequent analysis. We removed the initial 10s of each trial from the analysis to prevent biased conditions associated with the participants's calibration session. The data were filtered using a digital 4th-order low-pass Butterworth filter with a cut-off of 5 Hz. The analysis focused on various parameters of COP in the AP and ML directions. These parameters included displacement, mean velocity, root mean square (RMS), median frequency, circumference and rectangular area (representing 95% of the ellipse area of COP displacement).

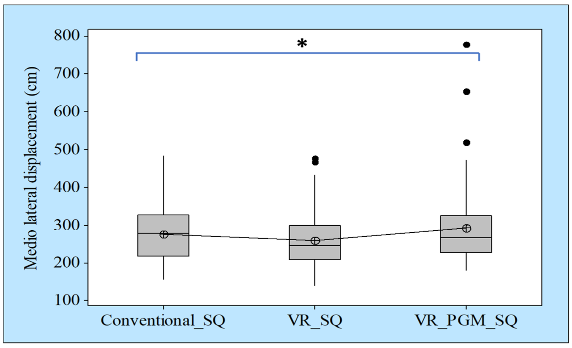

Fig. 5. ML displacement values of COP features during three squat conditions. *: $p < 0.05$.

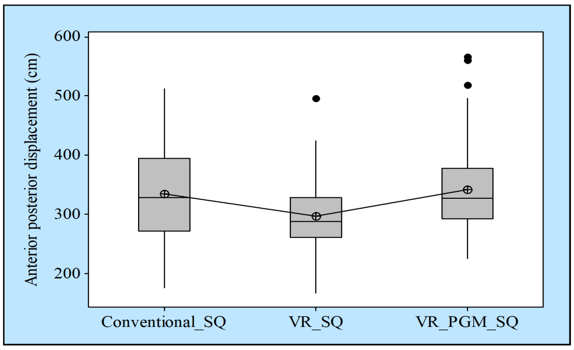

Fig. 6. AP displacement values of COP features during three squat conditions. *: $p < 0.05$.

V. RESULTS

A. Statistical analysis

We used the COP parameters for analysis to identify the body sway changes during the posture control gaming exercise while performing parallel or semi-squats. The statistical analyses were conducted using MINITAB 16.0. Before performing statistical analyses to identify the significant differences among three different squatting conditions, we performed interpolation and removed outliers using the advanced machine learning toolbox of MATLAB 9.12.0 (R2022a). We also tested the normality using the Kolmogorov-Smirnov, Shapiro-Wilk and Anderson-Darling tests. The obtained features were then subjected to one-way repeated measures analysis of variance (ANOVA) to compare baseline, VR-based squatting, and VR-combined PGM-based squatting conditions. The significance level (alpha, p) was set at 0.05.

The statistical analysis revealed a significant difference in the pairwise comparison of mediolateral displacement between the baseline and VR and PGM squatting session (F(2,15) = 2.98, p = 0.027) but no significant difference in anterior-posterior displacement between any groups (Fig. 5 and 6). For the root mean square (RMS), mediolateral pairwise comparison between the conventional squatting condition and VR squatting session (F(1,41) = 12.75, p = 0.001) and mediolateral pairwise comparison between the conventional squatting condition and VR and PGM squatting session (F(1,41) = 16.18, p = 0.001) revealed a significant difference (Fig. 9 and 10) but no significant difference in anterior-posterior displacement between both comparisons.

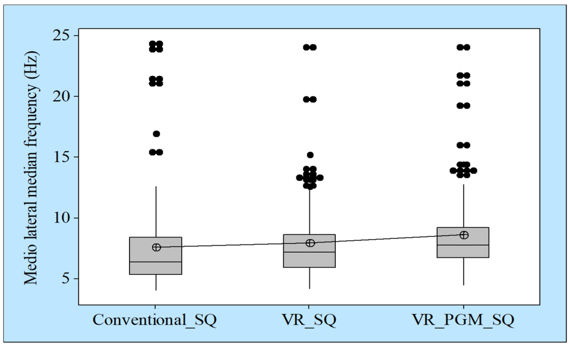

Fig. 7. ML median frequency values of COP features during three squat conditions. *: $p < 0.05$.

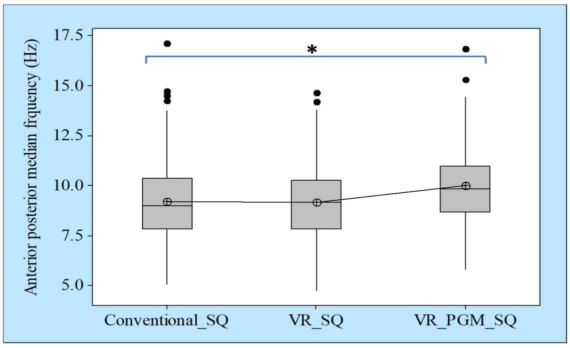

Fig. 8. AP median frequency values of COP features during three squat conditions. *: $p < 0.05$.

The ANOVA did not indicate any significant main effects for both pairwise comparisons of mean velocity (Fig. 11 and 12). Table II presented the values of mean and standard deviations of COP features obtained from statistical analysis. It was observed that there is no significant difference in the mediolateral median frequency parameter between both pairwise comparisons. In contrast, a significant difference was observed between the baseline and VR and PGM squatting session (F(2,07) = 7.20, p = 0.008) (Fig. 7 and 8). When considering the 95% ellipsoid sway area with rectangular measures revealed a significant effect of (F(2,07) = 5.76, p = 0.017) between the baseline and VR and PGM squatting condition (Fig. 13). With the circumference area measures, we can see the greater significant difference between both conditions: conventional - VR session (F(2,07) = 4.49, p = 0.035) and conventional- VR and PGM condition (F(2,07) = 18.42, p = 0.001) (Fig. 14).

VI. DISCUSSION

The hypothesis of this study is to investigate that the exercise-based game with multimodal feedback of visual-acoustic cues (VR) and position control-based haptic guidance (soft pneumatic actuators) would affect the body sway changes compared to the conventional squat training and the results of this study supported our hypothesis. From the results, the significant effect found in the mediolateral displacement between conventional and VR and PGM squatting sessions shows that combined haptic and augmented

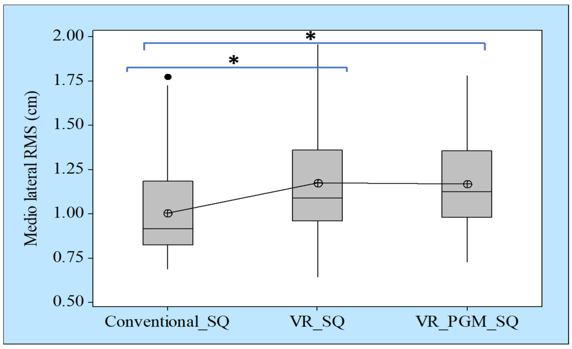

Fig. 9. ML RMS values of COP features during three squat conditions. *: $p < 0.05$.

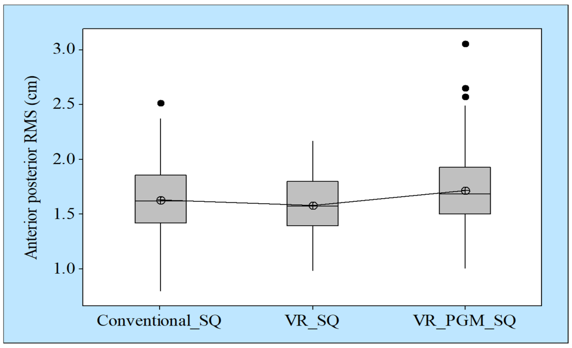

Fig. 10. AP RMS values of COP features during three squat conditions.*: $p < 0.05$.

visual feedback could provide adaptive postural control. These strategies for haptic guidance afford the user a degree of flexibility regarding position and/or timing. VR-based visual stimuli through adjustable movement speed changed the posture leading to a faster, variable and more adjustable body sway with increased mediolateral RMS. The perceived workload with the haptic cues enhances the postural control effectively based on the optimality principles of air pressure, completely restricting the deep squat posture movements in space and time.

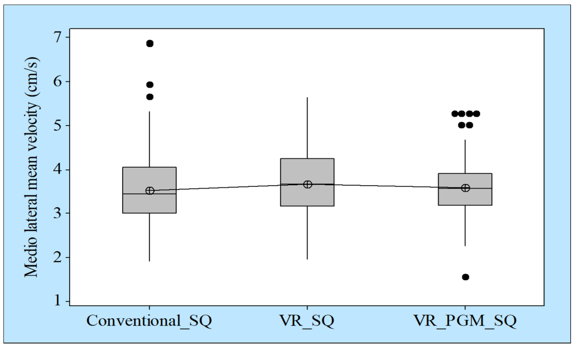

Fig. 11. ML mean velocity values of COP features during three squat conditions. *: $p < 0.05$.

TABLE II

MEAN AND STANDARD DEVIATIONS OF COP FEATURES FOR THREE USER GROUPS WHERE DS-DISPLACEMENT, RMS- ROOT MEAN SQUARE, RA- RECTANGULAR AREA, CA- CIRCUMFERENCE AREA, MF- MEDIAN FREQUENCY, MV- MEAN VELOCITY

COP		Baseline	VR	VR and PGM
DS	ML	275.44 ± 70.28	260.61 ± 70.41	303.37 ± 109.46
(*cm*)	AP	334.10 ± 79.06	296.77 ± 55.46	341.82 ± 74.16
RMS	ML	1.005 ± 0.246	1.172 ± 0.309	1.167 ± 0.235
(*cm*)	AP	1.625 ± 0.331	1.578 ± 0.281	1.720 ± 0.369
RA (cm^2)		71.97 ± 45.68	75.97 ± 39.12	87.66 ± 48.55
CA (cm^2)		33.76 ± 14.68	38.39 ± 16.74	8.452 ± 3.195
MF	ML	7.751 ± 4.015	8.039 ± 3.062	8.452 ± 3.195
(*Hz*)	AP	9.235 ± 2.148	9.154 ± 1.942	9.998 ± 1.947
MV	ML	3.641 ± 0.937	3.598 ± 0.764	3.567 ± 0.647
(cm/s)	AP	4.482 ± 1.061	4.377 ± 0.574	4.387 ± 0.706

There was also a significant effect in the sway area, primarily with the circumference area, proving that the system could be an effective tool for stabilizing the motion by providing vibrotactile and visual cues. The optimal control given to the soft actuators is a form of unexpected perturbation created when the user attempts to squat beyond the threshold set for performing parallel or semi-squats. The increase in median frequency shows that the user is trying to sync the motion with the collectible objects and adjusting body sway more rapidly to compensate for increased variability. Generally, increased postural sway velocity is associated with compromised balance and postural instability [16], [17]. There is no significant difference or increase in sway velocity, which shows the steady maintenance of posture according to the synchronization of pace to the movement of direction when the knee tremor increases. This may contribute to effective position control based on the user's skill level. The two types of feedback: haptic and augmented visual feedback are combined, they form a synergistic system that helps the user to achieve more effective postural control [18].

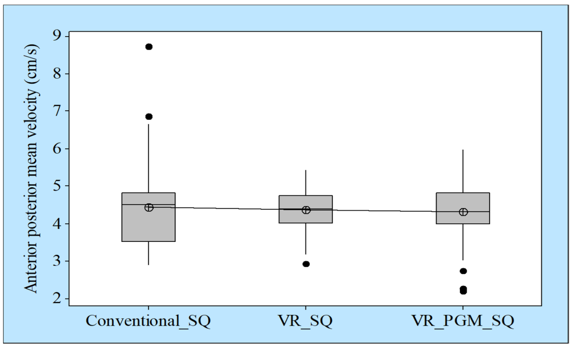

Fig. 12. AP mean velocity values of COP features during three squat conditions. *: $p < 0.05$.

Haptic feedback provides immediate cues for users to rapidly adjust their posture. Augmented visual feedback offers a broader view, helping users better understand their body's alignment with the environment. This study has some limitations. The study did not include impaired adults and older individuals, which might have given considerable correlative results. The study is also limited to major male users and fewer female users, Where the study lacks gender-based analysis on prototype usability.

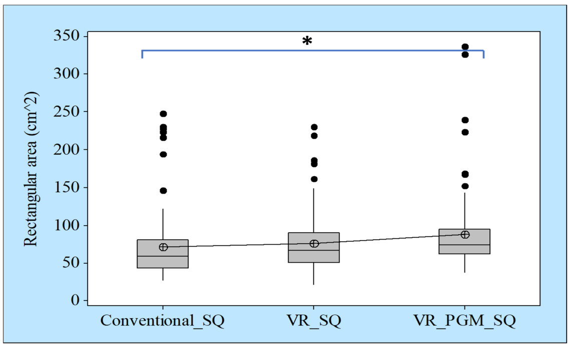

Fig. 13. Rectangular area values of COP features during three squat conditions. *: $p < 0.05$.

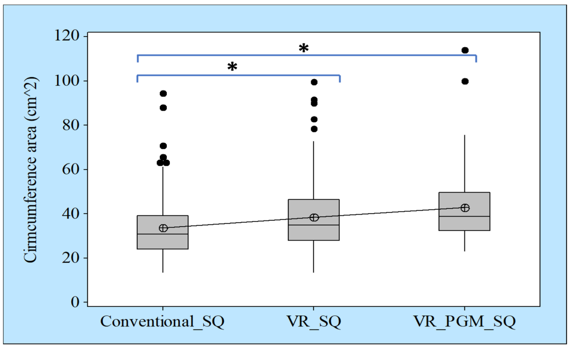

Fig. 14. Circumference area values of COP features during three squat conditions. *: $p < 0.05$.

VII. CONCLUSION

The study demonstrates that the combined effects of visual-haptic guidance could enhance reactive postural control and significant effects of COP features prove that perturbations or interventions are necessary to measure the postural stability. The primary advantage of VR-based programs is their ability to maximize exercise effects by capturing players' interest and full immersion in the games, distinguishing them from other exercise programs. The haptic cues the soft pneumatic actuators provide could be an added advantage for realizing reactive postural control.

ACKNOWLEDGEMENT

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