Adaptation and Training Effects from a Passive, Wearable Resistance Device During Exercise

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***Abstract*— The integration of technology into exercise regimens has emerged as a strategy to enhance normal human capabilities and return human motor function after injury or illness by enhancing motor learning. Much research has focused on how active devices, whether confined to a lab or made into a wearable format, can apply forces at set times and conditions to optimize injury prevention and proper movement. As a result, these devices tend to be confined to single movements or simple interventions. A focus on active forces, however, ignores the potential of continuous passive interactions. In this paper, we investigate how passive device behaviors by themselves can contribute to the process of training proper movement. Using a wearable resistance (WR) device, which is outfitted with elastic bands, we apply a force field that passively changes in response to full-body movements. We first develop a method to measure the produced forces from the device without impeding the function and we characterize the device's force generation. We then present a study assessing the impact of the WR device on overhead squat form compared to visual or no feedback. Our findings suggest that the force fields produced while training with the WR device could improve performance in full-body exercises more consistently compared to direct visual feedback, with effects seen on cross-body asymmetry. Our results provide insights into the application of passive wearable resistance technology in practical exercise settings.**

I. Introduction

As the field of human movement science has advanced, it has shown promise for enhancing and improving motor skills [1], [2]. Motor learning is defined as the natural acquisition and refinement of motor skills [3]. To artificially affect motor learning, feedback signals, including visual, auditory, and kinesthetic force cues, have been developed to facilitate skill acquisition and enhance movement precision and efficiency [4]. In particular, kinesthetic force feedback is an attractive and effective option for motor learning because it directly interacts with the physical aspects of movement execution and adaptation [5]. Traditionally, the study of motor learning and motion training through force feedback has relied on large, cumbersome kinesthetic force feedback devices to provide continuously controlled forces across all degrees of freedom of a target exercise [6], [7]. Properly designed kinesthetic force feedback devices facilitate motor learning even in the context of artificial restrictions, such as visuomotor rotations [8]. However, while these in-lab results hold potential to indicate how motor learning can be affected, their translation to real-world contexts has not yet been fully achieved.

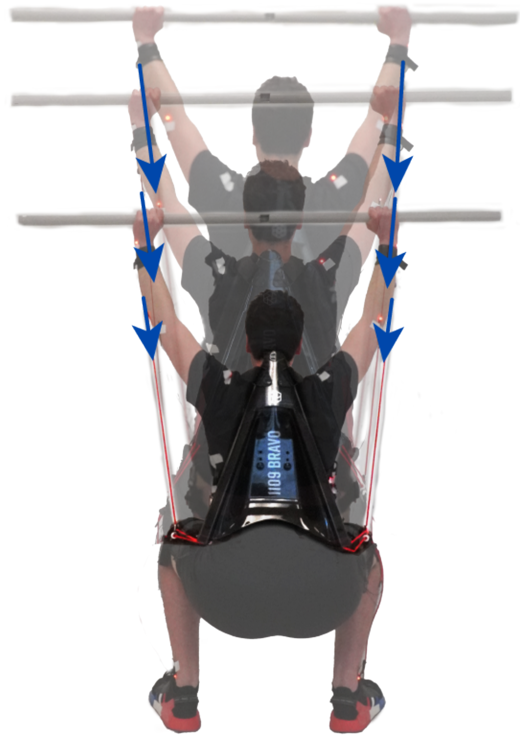

Fig. 1. An individual performing an overhead squat while wearing a wearable resistance (WR) device. The device applies force feedback through resistance bands. As the user squats down, the resistance force decreases.

Wearable devices have begun to address this gap by providing force feedback during more realistic and complex everyday motions. While some devices have been designed to actively control all degrees of freedom, most wearable devices choose to target specific joints or pieces of motion [9]–[11]. These wearable kinesthetic force feedback devices have demonstrated usefulness in rehabilitation [11]–[13], in reducing the metabolic rate and muscle fatigue during exercise [10], [14], and in improving personal fitness [15]. These works have focused on optimizing the force profiles for the active degrees of freedom, either to maintain human engagement [12] or to reduce metabolic costs [10]. Still, these devices often end up either overly complex or needing to be optimized for each given movement. Contrarily, looking to passive force application, resistive and plyometric exercise alone has been shown to help increase performance in sports such as tennis [16] and to increase neuromuscular fitness

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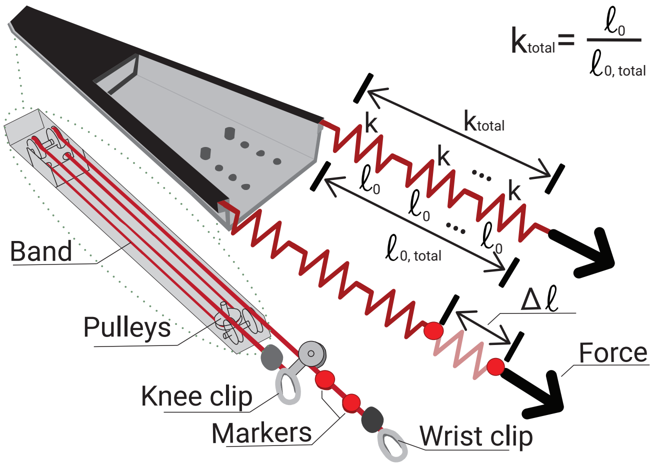

Fig. 2. Illustration of the wearable resistance (WR) device: (lower left) a cross-sectional view of one of the sides showcasing the resistance band wrapping around the pulleys and the knee/wrist clips, (right) an isometric view of the WR device is shown with the resistance bands presented as a series of springs showing the initial length of the location of the sewing of the markers, ℓ_0, the difference between the length of the motion capture markers throughout the exercises and length of the motion capture markers at rest, $\Delta\ell$, and the average between both of the band's calibration stiffness, k_{cal}.

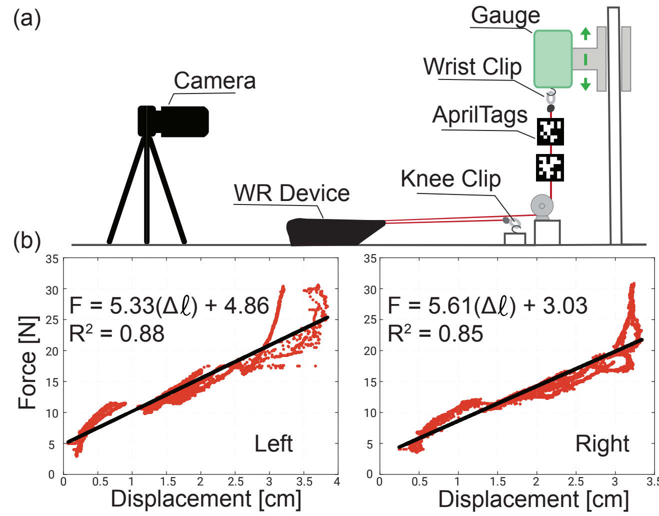

Fig. 3. The calibration experimental setup (a) and calibration results of the stretch sensor (b). (a) The force gauge (Series 7, Mark-10 Corporation, NY, USA), camera, AprilTag markers placement, wrist clip, and knee clip. (b) The force-displacement relationship for the stretch sensor, with separate lines representing the left ($F = 5.33 * \Delta\ell + 4.86[N]$, $R^2 = 0.88$) and right ($F = 5.61 * \Delta\ell + 3.03[N]$, $R^2 = 0.85$) sensors. The x-axis is displacement in cm, and the y-axis is force in N.

[17]. This suggests that properly designed passive force fields may yield some benefit to motor learning without needing to actuate each degree of freedom.

In pursuit of this, we examine the effects of the force field produced by a passive wearable resistance (WR) device throughout exercise (Figure 1). In Section II, we design and calibrate a stretch sensor to measure the forces generated by the WR device and show how these forces vary in practical exercise scenarios. Then, in Section III we present the results of a study on the application of the WR device during a single target exercise, overhead squats, and observe how users adapt to the device over time by measuring target biometrics. The concluding discussions reflect on the potential implications of these findings for both the field of motor learning and the practical deployment of WR devices in exercise.

II. Force Field of a Wearable Resistance Device

A. A Stretch Sensor for Resistance Bands

For this study, we used a WR device, the NeuroPak (1109 Bravo, KY, USA) designed to be used in a wide range of athletic activities (Figure 2), such as basketball, water polo, and ballet. The WR device is worn like a backpack, weighs 1.81 kg, and functions through a series of pulleys and elastic resistance bands (SGT KNOTS Supply Co., NC, USA) that connect from the backpack-like frame to straps placed around both the knees and wrists using clips. This setup uses clips from the frame to the knees to preload the elastic bands, ensuring a minimum tension in the band.

To measure the force applied by the WR device to the user's wrists, motion capture markers (Impulse X2E System. PhaseSpace, San Leandro, CA) are sewn to the WR device's bands to measure the band stretch. Considering the WR device's bands as a series of interconnected springs, we can use Hooke's law and, with the local displacement and band stiffness, obtain the resistance force applied, F. We measure the local displacement via these motion capture markers and a pre-calibrated band stiffness (discussed below). Since the marker positions did not exactly match the calibration length, the calibrated stiffness is corrected for the new resting length, resulting in this stiffness-displacement equation:

$$F = k_{cal} \cdot \frac{\ell_{cal}}{\ell_0} \cdot (\Delta\ell) + F_i \qquad (1)$$

where k_{cal} is the band's calibration stiffness, ℓ_{cal} is the calibration experiment segment length, ℓ_0 is the resting segment length between the motion capture markers with zero force applied, $\Delta\ell$ the relative stretch of the segment length throughout the exercises as measured by the motion capture markers, and F_i is the band's initial force observed in the calibration experiments. The same WR device with the same resistance bands was used in the calibration experiments and throughout the entirety of this paper to maintain consistency.

B. Calibration of the Stretch Sensor

A set of experiments were developed to obtain the resistance band stiffness. A force gauge (Series 7, Mark-10 Corporation, NY, USA) was employed to test the WR device's band at different force ranges. Using the setup shown in Figure 3(a), each resistance band (right and left side) was pulled in 4 overlapping force intervals to allow for a complete recording of the band's force-displacement behavior. Before data collection, the resistance bands were pre-tensioned with one of three tensile loading cycles at each of the 4 intervals. AprilTag markers provided exact measurements of the bands' elongation under different loading conditions. Videos were captured at 4k resolution at 30 fps on a commercially available camera (ZV-E10, Sony). Given that the band materials may be hyperelastic, the boundaries of

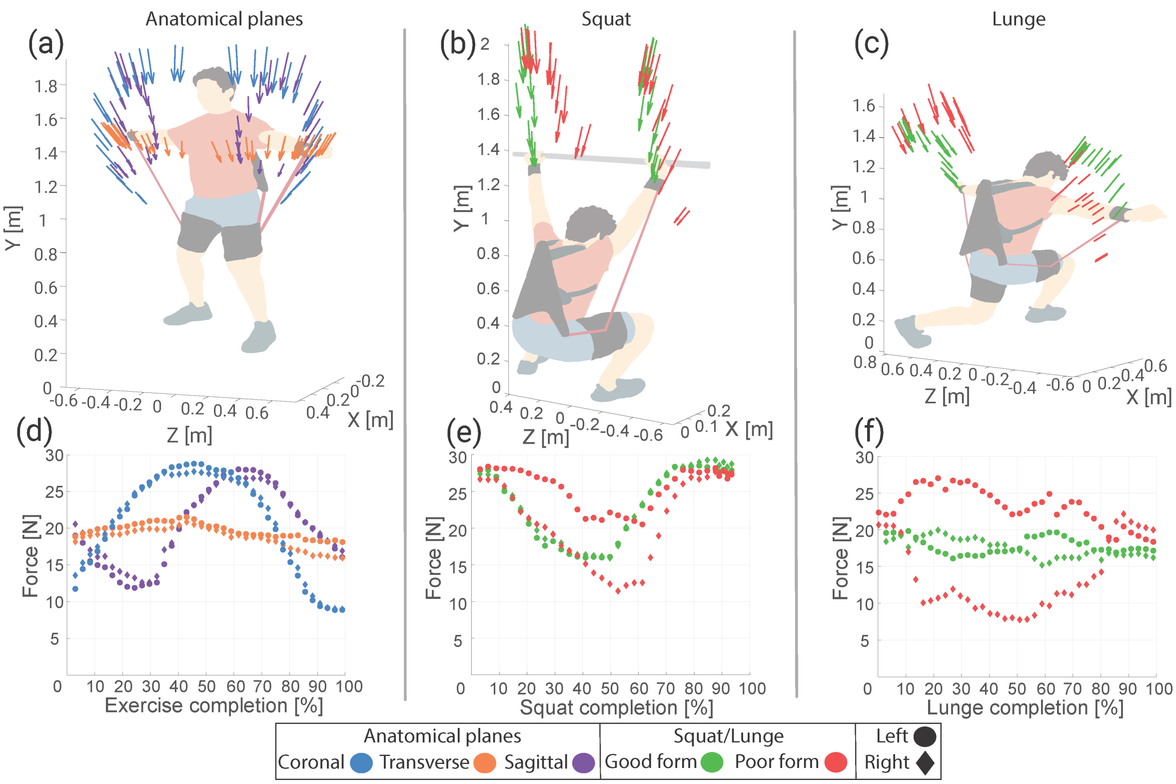

Fig. 4. (a) force vector plot of wearable resistance (WR) device while performing anatomical plane exercises (coronal/frontal, transverse, and sagittal) (b) force vector plot of WR device while performing overhead squats with good and poor form (c) force vector plot of WR device while performing extended arm lunges, with good and poor form (d) resistance band force over exercise completion percentage for anatomical plane exercises (e) resistance band force over squat completion percentage (f) resistance band force over lunge completion percentage

the experiment were expanded until the s-curve relationship emerged between the band's displacement and the force. The force-displacement data from the calibration experiment can be seen in Figure 3(b).

Due to the nature of this experiment, Equation 1 is set up to accommodate different lengths (ℓ_0) of the band while adjusting the resistance band stiffness. Additionally, we add an initial force to the stiffness equation, to account for the initial hyperelastic behavior of the bands. During use of the WR device, the bands are expected to maintain constant tension, so this linear calibration has high accuracy for the area of operation. Since there is no significant variation expected between bands, the right and left calibration variables, (ℓ_{cal}, F_i, and K_{cal}) were averaged and used for both sides.

C. Force Field Demonstration

With a developed stretch sensor and calibration, we established a series of exercises aimed at evaluating the device's functionality. This included a selection of two widely practiced workout exercises, modified to incorporate extended arm positions, thereby maximizing the impact of the WR device. A single 86 kg, 185 cm tall, male user familiar with the WR device performed these exercises. Each exercise in the routine was performed and analyzed once. The routine was composed of (1) quasi-static arm exercises, which were conducted in the coronal, sagittal, and transverse anatomical planes, and (2) dynamic exercises, specifically overhead squats, and extended arm lunges. For the overhead squat, the user of the WR device was told to perform a 90-degree angle squat. The quasi-static exercises provided a controlled environment to assess the range of forces exerted by the WR device, while the dynamic exercises allowed us to observe the device's performance in real-life, movement-based scenarios.

For the dynamic exercises, we paid particular attention to the comparison between good and poor forms, especially noting the impact of pelvic obliquity during overhead squats and extended arm lunges. In both the squat and lunge, a visually clear pelvic obliquity of zero and non-zero degrees was performed for good and poor form exercises respectively. Our analysis of the force vector plots revealed several key observations, Figure 4a-Figure 4c. Firstly, all force vectors were directed inward towards the user, corresponding to the direction of the resistance bands. We also noticed that the magnitude of these force vectors increased as the user raised their arms, while a decrease was observed whenever there was knee flexion in the dynamic exercises. Consistent forces were recorded between the left and right bands, except in instances where the dynamic exercises were performed with poor form.

The results from the individual exercises provided further insights into the characteristics of the force field generated by the WR device, Figure 4 d-Figure 4f. The coronal plane exercise demonstrated a negative sinusoidal force pattern, while the sagittal plane exercise displayed a bell-shaped force curve. The transverse plane exercise showed a constant force of around 20 N, consistent with the hands being maintained at chest level throughout the exercise.

The overhead squat exercise, when performed with good form, exhibited a negative bell-shaped force curve. However, when performed with poor form, the force patterns differed significantly between the left and right bands; the left-hand band displayed a positive bell-shaped force curve, and the right-hand band showed a negative bell-shaped curve. This difference in force application suggests the WR device's potential to assist with the correction of asymmetries in movement.

Similar observations were made in the lunge exercise. With good form, the force remained constant at about 18 N, attributed to the steady hand position near chest level throughout the exercise. In contrast, the lunge with poor form presented a disparity in force application, much like the overhead squat with poor form, with the left-hand band force showing a positive bell-shaped curve and the right-hand band a negative one.

D. Discussion

While wearing the WR device, the dynamic exercises performed with poor form showed an increase in force difference between left and right with increased pelvic obliquity angle, pulling the user back towards proper form, highlighting the device's capability to impose additional resistance in response to incorrect postures. This behavior mimics a force field that is proportional to error and provides assistance, thereby encouraging corrective action [18]. However, there is not merely a correlation with task error, as the forces in the WR device are also position-centric, and vary with symmetric motion as well.

With regard to the other exercises, we can see that the location of the hands significantly influences the average force between left and right in the full task space. Squatting shows similar forces to coronal arm movements and lunging shows similar forces to the transverse arm movements. This indicates that for normally performed exercises, the forces at the hands are similar to static force fields, exerting a position-dependent force, irrespective of user motion or trajectory. Prior research has also demonstrated that such force fields can improve proprioception, particularly in hand motion training [19].

The ability of this WR device to both challenge and guide users through physical resistance is similar to how traditional motor learning studies define assistive and static force fields. This strengthens our assertion of the WR device's capacity to provide passive force fields could offer the same benefits, over a broader range of motion.

III. Study on a Wearable Resistance Device's Effects in Squatting

This study was designed to provide a comprehensive evaluation of the impact of the WR device by comparing it to different feedback mechanisms during a standard exercise.

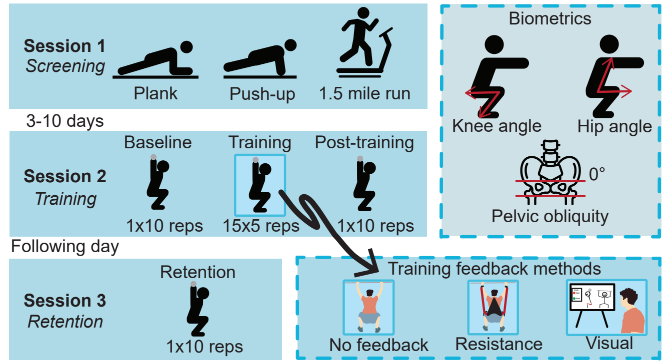

Fig. 5. Diagram of the study's timeline which includes: screening (session1), training (session 2), and retention (session 3). Session 2 involves performing a series of overhead squats: 1 set of 10 reps (baseline), 15 sets of 5 reps (training), and 1 set of 10 reps (post-training). Feedback methods for the training section are no feedback, resistance feedback, and visual feedback. The evaluated biometrics throughout the study are defined: pelvic obliquity, and knee/hip angles.

A. Hypothesis

For this study, we had two hypotheses: 1) the WR feedback will improve overhead squatting form compared to no feedback and on par with visual feedback, and 2) the improvements produced by the WR device will be retained after the feedback is removed.

B. Methods

We sought to evaluate the impact of the WR device (NeuroPak, 1109 Bravo, KY, USA) by comparing it to different feedback mechanisms and evaluating them for their effects in squatting form. We specifically focus on overhead squats performed by athletic individuals. Approved by Purdue University's Institutional Review Board (IRB #2022-1720), 36 subjects completed the entirety of this study, each voluntarily participating and fully briefed on the study's objectives and potential risks. Recruitment inclusion/exclusion criteria included subjects considering themselves generally athletic, with typical hearing and vision, and having no history of musculoskeletal or neurological disorders. Our experimental design was structured across three sessions (Figure 5, cumulatively spanning approximately 3.25 hours. Our primary goal was to assess and compare the efficacy of three feedback methods: no feedback, visual feedback, and resistance feedback.

The initial session functioned as a screening test. Here, subjects were required to provide basic demographic information and undergo a series of athletic screening tests based on the U.S. Air Force's physical fitness test (1.5-mile run, 2 minutes of hand-release push-ups, and a timed plank) [20] to evaluate each participant's physical fitness and suitability for the study (Table I). In the second session, those who got at least 90% of a passing score during the initial screening were assigned to one of the three experimental groups separated by feedback modality. Subjects then performed overhead squats while tracked by 20 motion-tracking markers (Table II and Figure 6). This session began with a baseline segment (1 set of 10 squats), followed by the training segment (15 sets of 5 squats) under the assigned feedback intervention,

TABLE I

DEMOGRAPHICS AND RESULTS OF ATHLETIC FITNESS TEST QUALIFYING SUBJECTS

	All	No feedback	Resistance	Visual
Subject [#]	36	12	12	12
Age [yrs]	22.6 ± 4.0	23.3 ± 4.5	21.9 ± 3.2	22.8 ± 4.1
Male [#]	28	11	8	9
Female [#]	8	1	4	3
90-100%	5 (all male)	2	2	1
≥100%	31	10	10	11

TABLE II

MARKER LOCATIONS

Marker [Left | Right]	Location
2 | 1	Ankle (top of lateral malleolus)
4 | 3	Lateral femoral epicondyle
6 | 5	Hip (iliac crest's most lateral aspect)
8 | 7	Side, mid axillary line, at R8
10 | 9	Shoulder side (3 fingers distal from acromion)
12 | 11	Elbow
14 | 13	Wrist (ulna carpal joint)
15	C4 spinous process
16	Sternum (sternal angle rib 3)
18 | 17	Sewn to band, close to knee
20 | 19	Sewn to band, close to wrist

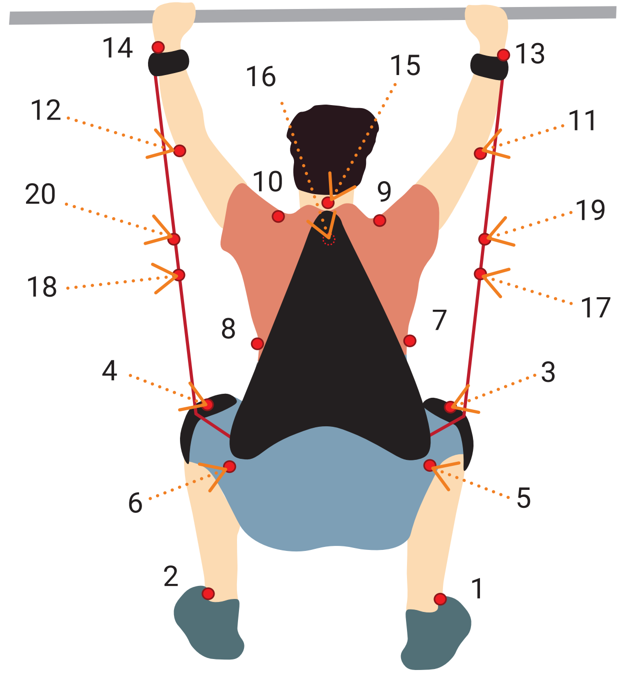

Fig. 6. Illustration of an individual using a wearable resistance (WR) device while performing an overhead squat. Motion capture markers are labeled in corresponding locations enumerated 1 through 20. Markers 17 through 20 are sewn on the WR device's resistance bands.

and concluded with a post-training segment (1 set of 10 squats). Subjects were instructed via a video to perform deep squats (knee angle of 100-120 degrees) and to maintain good form by maintaining an upright posture and symmetric form while doing so (controlling their hip angle). In addition, for their pelvic obliquity (angle/misalignment of the pelvis) subjects were asked to maintain it below 10 degrees offset. Subjects received a 5-minute break in between each segment. During the training segment, 30-second breaks were given in between sets. The following day, subjects reconvened for the third session, where they performed additional squats to test 24-hour retention (1 set of 10 squats). Out of the recruited subjects, all completed the screening and training, and only one subject failed to return for the retention session.

The feedback conditions varied solely during the training segment portion of the study. The resistance feedback group wore the WR device, which provided continuous forces during the overhead squat. The visual feedback group received feedback via a graphical user interface (GUI) at the end of each set of 5 squats during training. The GUI provided binary colored feedback (green representing good form and red representing poor form) for each of the three measures of form in the study. Visual feedback represents a good comparison as prior work has shown evidence for visual GUI feedback improving squatting form and motor learning [21], [22]. All biometric data was collected using motion capture, and an exit survey was administered to capture subjects' subjective feedback on their training experience.

C. Objective Measures

The motion capture system measured kinematic data during the overhead squat exercises. The study focused on several key biometrics, including knee angle, hip angle, and pelvic obliquity. These metrics were selected due to their relevance in assessing squat form. The three biometrics were approximated using the data from the motion capture markers as follows: knee angle, angle formed between ankles, knees, and hips markers; hip angle, angle between the chest, hip, and knee markers; and pelvic obliquity, angle between the two hips and the flat plane, referring to the angle/misalignment of the pelvis. From these measures, we also calculated and evaluated asymmetries between the left and right sides for knee angle difference, and hip angle difference, based on the observed effects of poor form in the single-user demonstration. These parameters assessed the quality of the squat, as they reflect the participant's ability to maintain balance, coordination, and proper body alignment throughout the movement.

D. Results

The performance metrics evaluated for all statistical tests were knee angle, hip angle, pelvic obliquity, knee angle difference, and hip angle difference. Statistical significance for all tests described below was defined at $\alpha = 0.05$. Data sets were tested for normality of distribution and equality of variances using the Kolmogorov-Smirnov test and Levene's test. In cases where data were not normally distributed or had unequal variances, non-parametric tests were used for specific hypothesis testing.

To evaluate changes from one set to another in each feedback group, the data across sections were examined for differences between the baseline, training start, training end, post-learning, and retention. Training start and end refer to

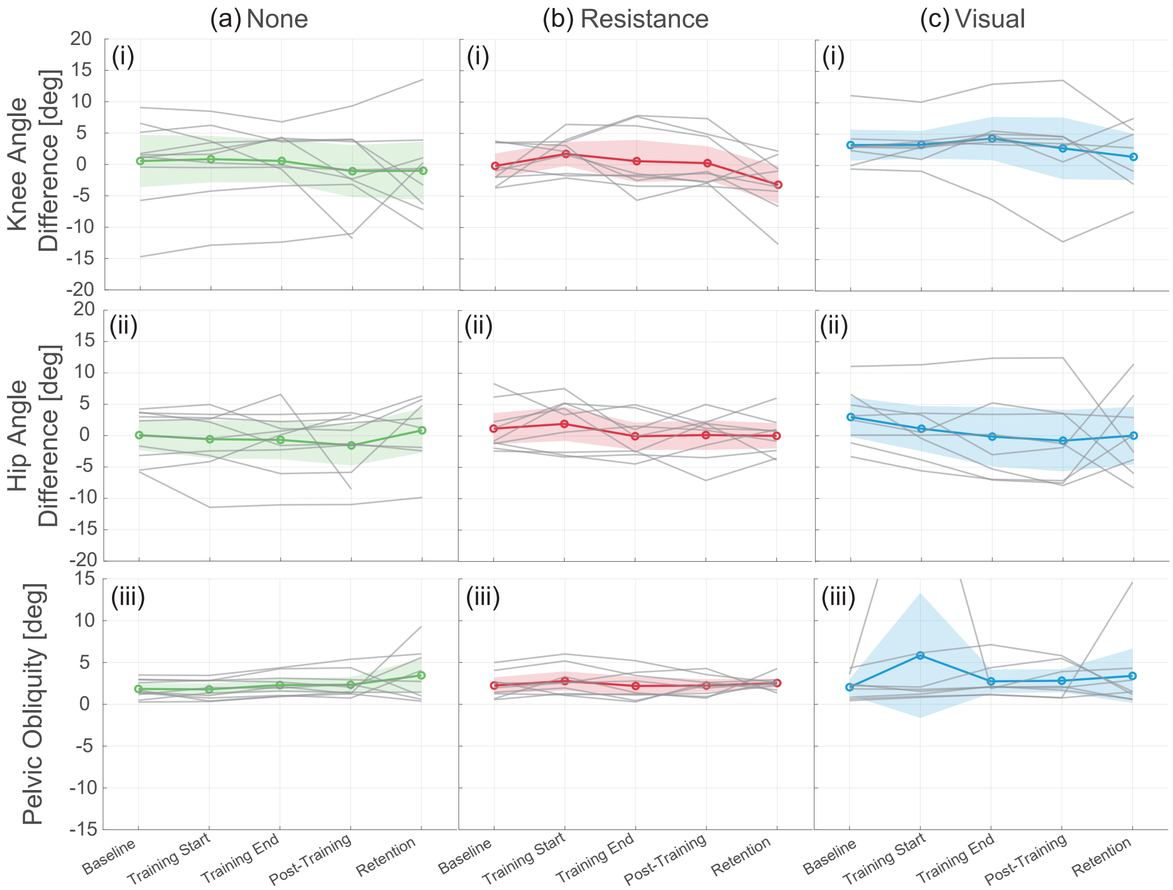

Fig. 7. Range of biometric asymmetry measurements from baseline through retention. Confidence interval plots are shown for different feedback types. The colored lines represent the average asymmetry value across all subjects in each feedback type: green for no feedback, red for resistance, and blue for visual. The colored shadows around the lines indicate the confidence intervals. Each grey line represents an individual subject. The plots include measurements for knee angle difference, hip angle difference, and pelvic obliquity across various stages: baseline, training start, training end, post-training, and retention.

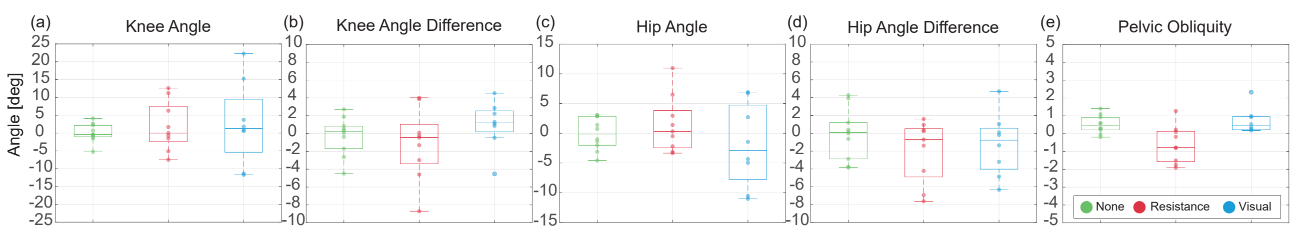

Fig. 8. Change in measurements from training start to end. This box and whisker plot illustrates the variations across three feedback types: no feedback (green), resistance (red), and visual (blue). For each box, the central line represents the median, the edges of the box indicate the 25th and 75th percentiles and the whiskers extend to the most extreme data points not considered outliers. Subjects are represented by dots, with outliers highlighted in a noticeably darker shade. The subplots display changes in knee angle, knee angle difference, hip angle, hip angle difference, and pelvic obliquity.

the first and last 2 sets of the 15 sets performed in the training segment of the experiment. Data were tested for significant differences for each biometric using ANOVA for parametric data and Kruskal-Wallis for non-parametric data. Knee and hip angle were evaluated for range of motion and knee angle difference, hip angle difference, and pelvic obliquity were evaluated for asymmetry measures. No significant differences were found in range of motion or asymmetry measures within any group. To evaluate the effects of feedback methods, changes across sets were tested for no feedback vs. resistance feedback vs. visual feedback. Additional ANOVA and post-hoc Tukey tests were run to compare no feedback vs. visual feedback vs. resistance feedback data sets for changes from baseline to training start, baseline to post-training, baseline to retention, and training start to training end, averaging the performance over equal sets of 10 overhead squats for each section. Knee and hip angle differences were treated as the absolute value of the asymmetry (disregarding which side is favored) to evaluate the absolute improvement of asymmetry. Knee and hip angle differences were also tested with relative values of the asymmetry to register the overcorrection of a participant from one side to another (Figure 7).

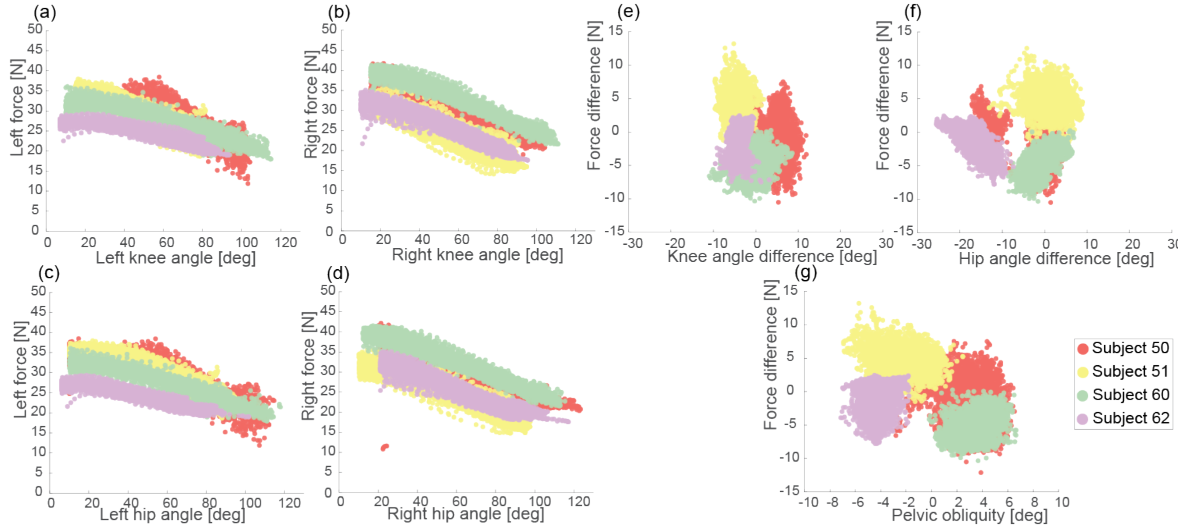

Fig. 9. Force applied to the subject during overhead squat training as a function of knee angle and hip angle. (a)-(b) Left and right knee angle versus force respectively. (c)-(d) Left and right hip angle versus force. Difference in the right and left forces applied to the subject during overhead squat training over (e) knee angle asymmetry, (f) hip angle asymmetry, and (g) pelvic obliquity.

While no significant differences were found in any of the pairwise tests, trends of improvement or worsening of form could be seen in the data (Figure 8). Improvements in form were defined as an increase in range of motion measures (knee and hip angle) and a decrease in asymmetry measures (knee angle, hip angle, pelvic obliquity). A trend in worsening form was seen in the resistance feedback group from baseline to training start compared to visual and no feedback. A general trend in greater improvements in form from training start to training end was seen in resistance feedback compared to visual and no feedback. From baseline to post-training, there were greater improvements in resistance feedback for range of motion measures, but asymmetry measures were not consistent. Knee angle difference and pelvic obliquity increased while hip angle difference decreased. From baseline to retention, there were improvements in range of motion in the resistance and visual feedback groups compared to no feedback, but resistance feedback exhibited the greatest increase in knee angle difference and the greatest decrease in hip angle difference.

E. Force Analysis Results

In addition to the objective measures described above, we measured the force applied to participants during the experiments. Due to issues with motion capture markers and occlusions, only 4 of the WR subjects have sufficient force data to analyze during the training segment (Figure 9). The force range (between 10-40 N) was perceptible by the subjects based on the post-study survey, providing kinesthetic feedback. The data revealed a clear pattern matching with the results in Section II: the force applied was lowest when the knee and hip angles were approximately 90-120 degrees, corresponding to the deepest squatting position. As the angles widened towards 0-20 degrees, indicating a return to a standing position, the force increased.

We also examined the force differences (between left and right sides) in relation to asymmetries such as knee and hip angle differences, and pelvic obliquity (Figure 9). Our findings indicated that knee angle difference did not influence the force difference during squatting. Similarly, the relationship between pelvic obliquity and force difference was not pronounced, which is not aligned with the differences seen during the poor form squat in Fig. 4e. This indicates that the force changes for squat asymmetries may be more complex than the three biometrics calculated.

F. Discussion

The qualitative analysis of results and force analysis of the experiment suggest that the WR device produces changes in overhead squat performance when compared to no feedback, but these changes are not significant. This supports our first hypothesis, that passive WR devices can improve squatting form on par with active feedback like the visual feedback condition. However, these changes are not consistent for all measures. Interestingly, putting on the WR device initially seems to cause a worse performance, likely due to subjects needing to adjust to the increased resistance. However, by the end of the training segment, the WR group had on average increased performance in four out of five calculated biometrics, compared to the no feedback group that saw no change or worsening on all metrics and the visual group that only improved one metric. This is especially interesting given that the visual feedback group had explicit feedback on three metrics. Potentially, the performance on the knee and hip angle may have started sufficiently high that there was little room for subjects to improve in the visual group, and without any feedback related to their asymmetries they were unable to improve their performance on them. This suggests that the force feedback from the WR device seems to give sufficient signals during training to remove asymmetric motions and even improve squat depth if instructed. This conclusion is further supported by subject survey comments such as "I think the resistance feedback helped make bad form harder to do. It also made squats without feedback much easier as there was no resistance" and another saying that the WR device was "Good for strength training that is not evident/noticeable when working out". Further testing with subjects with a range of athletic abilities may be able to clarify whether training improvements are stronger on asymmetric measures or possible on all exercise measures. These results suggest that the WR passive force field can stimulate improvements in form, so a passive force field designed for an exercise may yield benefits for a wearable device.

The second hypothesis is not supported by the statistical or force results. There are no significant results seen in the behaviors before and after the training, despite seeing the differences emerge for some WR feedback subjects during training. Potentially this indicates that the washout period (i.e. amount of time to unlearn a learned behavior) for the improvements was too short to notice when averaging ten overhead squats together, potentially due to the high average fitness level of all participants. From a post-experiment survey, over 90 percent of subjects were familiar with squats and worked out more than 3 days a week, suggesting subjects were already used to squatting in a certain form and a single intervention was not enough to see a retained change in form.

IV. Conclusion and Future Work

In this work, we have demonstrated that a passive wearable resistance device can produce force fields with analogs to those seen in motor learning research. These force fields can also induce changes in the performance of full-body exercises when compared to with no feedback. These results suggest that passive force fields may be a beneficial alternative or addition to active feedback devices for motor learning. However, the improvements in squatting were not retained after training and were not consistent across all metrics, indicating that more thought is needed on how to design passive force fields to yield longer results.

In the future, we plan to test these results against other exercise conditions by varying the target exercise and by testing in less athletic populations. Additionally, we will investigate how this force field can be tailored to an exercise or to an individual subject and how the results can support active force feedback devices.

V. Acknowledgements

The authors thank the Purdue Ismail Center Staff, Jordan Lyles, and Aaron Farha for help throughout the study.

References

[1] N. Shishov, I. Melzer, and S. Bar-Haim, "Parameters and measures in assessment of motor learning in neurorehabilitation; a systematic review of the literature," *Frontiers in human neuroscience*, vol. 11, p. 82, 2017.

[2] X. Zhang, G. Shan, Y. Wang, B. Wan, and H. Li, "Wearables, biomechanical feedback, and human motor-skills' learning & optimization," *Applied Sciences*, vol. 9, no. 2, p. 226, 2019.

[3] B. Tassignon, J. Verschueren, J.-P. Baeyens, A. Benjaminse, A. Gokeler, B. Serrien, and R. Clijsen, "An exploratory meta-analytic review on the empirical evidence of differential learning as an enhanced motor learning method," *Frontiers in psychology*, vol. 12, p. 533033, 2021.

[4] R. Sigrist, G. Rauter, R. Riener, and P. Wolf, "Augmented visual, auditory, haptic, and multimodal feedback in motor learning: a review," *Psychonomic bulletin & review*, vol. 20, pp. 21–53, 2013.

[5] H. Culbertson, S. B. Schorr, and A. M. Okamura, "Haptics: The present and future of artificial touch sensation," *Annual Review of Control, Robotics, and Autonomous Systems*, vol. 1, pp. 385–409, 2018.

[6] J. Lee and S. Choi, "Effects of haptic guidance and disturbance on motor learning: Potential advantage of haptic disturbance," in *IEEE Haptics Symposium*. IEEE, 2010, pp. 335–342.

[7] E. Basalp, P. Wolf, and L. Marchal-Crespo, "Haptic training: Which types facilitate (re)learning of which motor task and for whom? answers by a review," *IEEE Transactions on Haptics*, vol. 14, no. 4, pp. 722–739, 2021.

[8] D. P. Losey, L. H. Blumenschein, J. P. Clark, and M. K. O'Malley, "Improving short-term retention after robotic training by leveraging fixed-gain controllers," *Journal of rehabilitation and assistive technologies engineering*, vol. 6, p. 2055668319866311, 2019.

[9] J. Park, D. H. Kim, S. Hyung, G. Shin, Y. G. Kim, S.-H. Kim, C. Yoon, S. Ko, K. Hahm, and M. Lee, "Design of a cable driven wearable fitness device for upper limb exercise," in *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. IEEE, 2023, pp. 6456–6461.

[10] L. Chen, C. Chen, Z. Wang, X. Ye, Y. Liu, and X. Wu, "A novel lightweight wearable soft exosuit for reducing the metabolic rate and muscle fatigue," *Biosensors*, vol. 11, no. 7, p. 215, 2021.

[11] B. C. Conner, M. H. Schwartz, and Z. F. Lerner, "Pilot evaluation of changes in motor control after wearable robotic resistance training in children with cerebral palsy," *Journal of biomechanics*, vol. 126, p. 110601, 2021.

[12] A. A. Blank, J. A. French, A. U. Pehlivan, and M. K. O'Malley, "Current trends in robot-assisted upper-limb stroke rehabilitation: promoting patient engagement in therapy," *Current physical medicine and rehabilitation reports*, vol. 2, pp. 184–195, 2014.

[13] J. Kim, F. Porciuncula, H. D. Yang, N. Wendel, T. Baker, A. Chin, T. D. Ellis, and C. J. Walsh, "Soft robotic apparel to avert freezing of gait in parkinson's disease," *Nature medicine*, pp. 1–9, 2024.

[14] K. L. Poggensee and S. H. Collins, "How adaptation, training, and customization contribute to benefits from exoskeleton assistance," *Science Robotics*, vol. 6, no. 58, p. eabf1078, 2021.

[15] J. Park, J. Kim, D. H. Kim, J. Hwang, Y. G. Kim, S. Hyung, S.-H. Ko, and M. Lee, "Design of a soft wearable passive fitness device for upper limb resistance exercise," in *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. IEEE, 2022, pp. 8488–8493.

[16] M. Centorbi, G. Fiorilli, G. Di Martino, A. Buonsenso, G. Medri, C. della Valle, N. Vendemiati, E. Iuliano, G. Calcagno, and A. di Cagno, "Resistance training using flywheel device improves the shot precision in senior elite tennis players: A randomized controlled study," *Applied Sciences*, vol. 13, no. 24, p. 13290, 2023.

[17] D. Novak, I. Loncar, F. Sinkovic, P. Barbaros, and L. Milanovic, "Effects of plyometric training with resistance bands on neuromuscular characteristics in junior tennis players," *International Journal of Environmental Research and Public Health*, vol. 20, no. 2, p. 1085, 2023.

[18] S. Israely and E. Carmeli, "Error augmentation as a possible technique for improving upper extremity motor performance after a stroke–a systematic review," *Topics in stroke rehabilitation*, vol. 23, no. 2, pp. 116–125, 2016.

[19] D. J. Goble and J. A. Anguera, "Plastic changes in hand proprioception following force-field motor learning," *Journal of neurophysiology*, vol. 104, no. 3, pp. 1213–1215, 2010.

[20] "Us air force fitness program." [Online]. Available: https://afpc.af.mil/Career-Management/Fitness-Program/

[21] S. Bonnette, C. A. DiCesare, A. W. Kiefer, M. A. Riley, K. D. B. Foss, S. Thomas, J. A. Diekfuss, and G. D. Myer, "A technical report on the development of a real-time visual biofeedback system to optimize motor learning and movement deficit correction," *Journal of Sports Science & Medicine*, vol. 19, no. 1, p. 84, 2020.

[22] E. Kal, T. Ellmers, J. Hogg, A. B. Slutsky-Ganesh, S. Bonnette, S. Thomas, C. D. Riehm, G. D. Myer, and J. A. Diekfuss, "Optimal training for movement acquisition and transfer: Does "externally focused" visual biofeedback promote implicit motor learning?" *Journal of Athletic Training*, vol. 58, no. 7-8, pp. 648–654, 2023.