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Weight-Mate: Adaptive Training Support for Weight Lifting

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ABSTRACT

Weightlifting is easy to learn, but difficult to master. People who do weightlifting do it to improve their health, strengthen their muscles and build their physique. However, due to the complex and precise body positioning required, even experienced weightlifters require assistance in perfecting their technique. At the same time, the training requirements of the individual change over time, as they perfect and hone their craft. To help weightlifters achieve optimum personal performance, we designed *Weight-Mate*, a prototype wearable system for giving weightlifters of different skill levels personalized, precise and non-distracting immediate feedback on how to correct their current body positioning during deadlift training. By iterating *Weight-Mate* using cooperative usability testing (CUT) with weightlifters of different competencies with their coaches we designed a system that could adapt to individual physiology and training needs. The *Weight-Mate* sensor suit maps the lifter's body configuration against the ideal deadlift position throughout all stages of the life, as defined by their coach, and provides non-intrusive feedback to the lifter to correct their body position. Our formative evaluation with ten weightlifters shows that an adaptive approach to digital weight training offers great promise in assisting weight lifters of all levels to improve their technique, and hence improve the safety of the sport.

CCS CONCEPTS

• Human-centered computing~Interface design prototyping

KEYWORDS

Assistive training technologies, Adaptive systems, Interaction design, Wearables, Weightlifting, IMU sensors, User feedback.

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1 Introduction

Weightlifting improves health and strengthens body muscles, but technique in a weightlifting exercise is of the utmost importance in order to obtain the full efficacy of the exercise and to improve performance. The deadlift exercise demands excessive concentration by the lifter, because the exercise enables several joints to be engaged and strengthened, to build competence and avoid injuries. Weightlifters often refer to the deadlift as "the King of all exercises". Weightlifters aim to push their bodies beyond current physical capabilities by continually increasing the weight they can lift. While doing a deadlift, the lifter is in a high-stress situation, both physically and mentally, and needs to fully concentrate on their body state. Any external feedback providing corrective posture assistance needs to be non-distracting, to not break the lifter's intense concentration toward completing a correct and safe deadlift.

Experienced weightlifters, in particular, provide an interesting study in the development of assistive training technology because they are pushing their physical capabilities to their personal limit and beyond. They do the deadlift under immense physical and psychological pressure, and sometimes their concentration and stress levels are so intense that they can even lose consciousness - a potentially harmful situation if they are lifting heavy weights. At the same time, people in these high concentration situations benefit from personal training assistance to refine their posture and help them make small physical adjustments that positively impact their performance.

There are very few research studies in the area of wearables and other emerging technologies designed to assist in weightlifting, particularly with a focus on personalized support for all levels of lifters in refining their technique. However, there are several studies using these technologies to support other physical activities such as exercising, martial arts, and physiotherapy. These studies are mostly focused on novices learning to do a new activity or monitoring fairly repetitive or safe motions.

The idea of training support for people at all levels of expertise in their sport, and under intense psychological and physical pressure is a new area of investigation. There is an opportunity in adaptive and assistive training technologies for designing novel approaches to weightlifting assistance. To this end we have designed and studied in use, a system that models an individual's body configuration, and tracks their movements during a deadlift to provide non-intrusive and useful feedback that adapts to their current training level. This helps them to correct their technique during the activity of lifting potentially heavy weights, allowing them to push to the extreme end of their current capabilities, even when their coach is not present to ensure the physical benefits and safety of the lift.

In this paper, we survey related work, describe physical requirements of the deadlift, report on three iterations of design and evaluation of our prototype, and discuss the implications of our findings toward developing adaptive training systems.

2 Related Work

In this section, we present research in related areas of motion capture and assistive feedback, and technology in weightlifting.

2.1 Camera Tracking

Depth motion cameras, such as Microsoft Kinect, are used extensively in research on body tracking systems. Substantial research has shown how the camera can be used to track users' movement and body position. Anderson et al [2] describe YouMove, a system that enables the user to record and learn sequences of body movements with a Microsoft Kinect. The user is guided using an augmented mirror which overlays the user with a stick figure showing the movements to be learned. Using a Root Mean Squared Error on the distance difference from the user's movement to the target movement, they revealed that YouMove had an average distance difference of 0.10 m corresponding to improved movement of 44%. A video demonstration of the same movement, only gave a 20% improvement. Additionally, YouMove had a greater retention rate of learned movements than the video demonstration. However, the YouMove system fails to track particular body positions when the user is moving toward the camera. This implementation also requires a large mirror facing the user, making it difficult to move to different training locations. However, it indicates that augmentation is an effective way of providing feedback to users.

Another example of augmentation is using computer-generated graphical overlays on a real-time camera feed of the user shown on a screen. This was shown by Tang et al. [15] to successfully give immediate feedback to the user in the case of remedial physiotherapy. Their system, Physio@Home, allows the user to perform their prescribed exercises at home using two Kinect cameras. One camera tracks the front and the other is positioned above the user. Feedback is given in the form of red and green coloured arcs, guiding the correct positioning of limbs in the exercise. Through a study of use, Tang et al. found that the feedback arcs combined with multiple views was the most accurate guidance. However, the implementation requires two cameras, reducing portability. Additionally, camera markers were not always visible, creating instability of body tracking.

This shows that although cameras can accurately track most movements, this accuracy is lost when the user stands in certain positions or if obstacles are in the way. To alleviate this problem, Velloso et al. [19] propose MotionMA, which enables the user to record and learn body movement sequences. However, instead of relying solely on a Kinect camera, MotionMA also utilizes on-body sensors to measure the orientation of upper and lower arm. MotionMA has a record and learn interface, which was positively received by the weightlifters with respect to the accuracy of the demonstrated movement. However, the MotionMA system does not track hands and feet accurately enough, and is limited in its ability to tell if a hand is open or closed. Also, if the user is facing the camera with limbs pointed toward it, the camera cannot track the movement.

2.2 On-Body Sensor Tracking

The use of on-body sensors to detect and recognize movement patterns can be found in several studies. Of note, this technology has been proven to reliably recognizing full body movement patterns. Kowsar et al. [8] proposed a system to detect unseen anomalies in weight training exercises based on a dataset of body motion data from Magnetic Angular Rate and Gravity (MARG) sensors (accelerometer, gyroscope and magnetometer) placed on stomach, lower and upper arm. They found that the system could detect anomalies in weightlifting using only the accelerometer with 98% accuracy, demonstrating the potential of Inertial Measurement Units (IMUs). They also demonstrated the potential of processing just one movement axis of data during the weightlifting exercise. This inspired us to see if the deadlift could be recognised using one movement axis for our design.

One advantage of on-body sensors is that a screen is not always necessary to provide feedback. Ananthanarayan et al. [1] designed PT Viz, a system for knee rehabilitation exercises. With PT Viz, the user wears a knee sleeve with sensors in it, over the thigh and calf. The sleeve incorporates a sensory display with green light strips over the thigh, indicating the range of motion of the knee. Users responded positively to the wearability and portability of PT Viz. One user suggested that fine grained light strips would be an improvement, in order to identify more subtle improvements of the exercises.

2.3 Feedback in Sports Training

In HCI literature, there are several studies of people who interact with technology in mentally stressful situations, for example, air traffic control [3]. However, research on receiving feedback under physical pressure is scarce.

Looking at feedback generally in sports training, there are a number of interventions used to improve athletic skills and performance, , such as in gait retraining using inertial sensors and visual feedback, such as gait retraining using inertial sensors and visual feedback [18]. Researchers have had success using video feedback and video modeling when applied in an athletic training setting [11]. Coaching packages successfully include aspects such as: verbal instructions; modeling by a coach, peer or expert; opportunity for practice of the skill; and verbal feedback. A coaching system for weightlifting, therefore, could conceivably use a variety of feedback mechanisms. However, it is speculated that too much feedback while under pressure may hinder the weightlifter in making use of it, and make the activity unsafe. In designing systems to support weightlifting training, it is important to recognize that subtle movements require intense concentration under the physical pressure of heavy weights.

2.4 Adaptive Interactive Training Systems

There is little work in interactive adaptive systems for physical training. Much of the recent work in adaptive technologies is in the fields of robotics [16] and VR gaming [13, 20], however, research into training adaptation from an HCI perspective showed that giving the user information about their current exertion levels assisted in adapting training intensity [17].

3 Anatomy of the Deadlift

In this section, general body anatomy is briefly described as well as the physical requirements of the deadlift.

3.1 Body Anatomy

In order to describe and understand the deadlift exercise certain knowledge is needed about the anatomy of the human body and its movements. The movement of a body can occur in many directions and its analysis is performed in three perpendicular planes including the Sagittal (anterior-posterior), Frontal (medial lateral), and Transverse (figure 1). In addition, the body can be divided into head, neck, upper limbs (from shoulder to hand), lower limbs (hip to foot), and trunk (the back, chest, abdominal, loin and pelvis) [9].

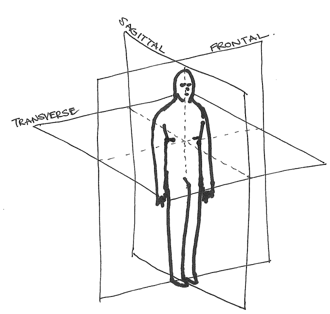
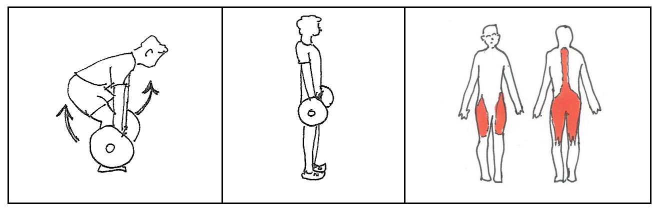


Figure 1: The human body divided into frontal, sagittal and transversal plane.

Biomechanical analysis of the body segments is performed in both linear and angular motion. Angular movements are the most prevalent in the deadlift, and primarily performed in the sagittal plane. In the sagittal plane, the joints can flex i.e bend, by decreasing the angle between the adjacent segments in action. The counter movement to flexion is extension, in which the angle between adjacent segments increases. In the frontal plane, angular joints are considered to adduct by decreasing the angle between the segment and the midsagittal line. The counterpart to adduction is abduction, which in contrast is increasing the angle between the segment and the midsagittal line [9]. Both flexion and abduction are prime movements in the deadlift.

3.2 The Deadlift Exercise

The deadlift exercise starts with flexing the hips, knees, and ankles, with shoulders vertically aligned with the barbell (figure 2a). The weightlifter then lifts the barbell by extending the hips, knees, and ankles to a standing posture position (figure 2b). The prime muscles engaged in this compound weightlifting exercise are hip extensors (Gluteus Maximus, hamstrings), knee extensors (quadriceps), lower back (erector spinae), and upper extremity (trapezius) (figure 2c). The deadlift was chosen for this study because it is a weightlifting exercise that engages multiple joints and yet is safer than others as the weightlifter can simply let the barbell go when reaching failure, without injury [14].



(a) (b) (c)

Figure 2: Performing the deadlift, with (a) start position (b) end position, and (c) the muscles engaged (front & back).

4 The Study

To study provision of adaptive feedback under physical pressure in weightlifting, we iteratively developed and evaluated the *Weight-Mate* system. It is built using the Unity game engine and a compression suit fitted with sensors that are aligned on legs, trunk, shoulders, and arms using the FLORA wearable electronic platform.

We used the Cooperative Usability Testing method (CUT) [6] to evaluate our prototypes during three development and evaluation iterations. This was chosen to avoid the need for think-aloud testing in this kind of situation, where the test participant is under both psychological and physical pressure while using the system, and so needs to concentrate completely on the lift. CUT is divided into two sessions. An interaction session, where the test user is using the system, and an interpretation session, where evaluators and test users discuss important interaction problems encountered by the user while watching a video of the interaction session. All evaluation sessions were conducted in Danish.

Our study was conducted in four phases: initial design followed by three iterations with development and formative evaluation with users. During the initial design phase, we investigated sensor technologies and Unity to see how they could be combined with our own design ideas [14] and related work in this area, to create a system to adaptively provide feedback for a weightlifter performing the deadlift. In the first iteration, the prototype, was designed for lower limbs only, and evaluated with 3 weightlifters. In the second iteration, we refined the prototype by implementing sensors for all body parts, and designing a wearable suit based on the formative evaluation from the first iteration. This second version of the prototype was then evaluated with 3 weightlifters. The third prototype of *Weight-Mate* was designed based on evaluation results and user feedback from the second iteration. A third evaluation, focusing on adaptation and feedback, was then conducted with ten weightlifters of varying skill levels, performing the deadlift lifting their personal maximum weights. The following provides detailed descriptions of each of these phases.

4.1 Initial Design Phase

In our previous work [14], three different exploratory prototypes were designed based on interviews with three weightlifters, a physiotherapist and a coach. Coaching for weightlifting frequently involves verbal instructions in combination with modeling of the skill by the coach. Talking to the coach gave us insight into the feedback typically provided before, after and during a deadlift, and how that changes depending on the level of the lifter. The physiotherapist gave us insight into proper lifting techniques and an account of typical injuries resulting from poor technique. After evaluating the three prototypes, we found that optimal feedback was provided using visual feedback to adjust the start position before the lift. During the lift, weightlifters responded best to audio feedback. After the lift, they wanted visual feedback showing their performance during different repetitions of the set.

We created the initial prototype using IMUs for tracking body movements. This was to avoid limitations identified in related work with depth motion cameras. We were also concerned about portability issues, including the need for correct light settings and camera positioning, and avoiding handheld weights obstructing the camera view.

We tested the performance of different fusion filters, including the Madgwick MARG, Mahony and Kalman filters and chose Kalman filters as they provided the most precise and responsive motion data. During this testing, we also found that roll motion for start positioning (in the frontal plane) and pitch motion during the exercise (in the sagittal plane) were sufficient to represent the deadlift, as shown by Kowsar et al. [8] using the axis of effect. This simplified implementation as yaw motion (in the transverse plane) proved inaccurate with our setup.

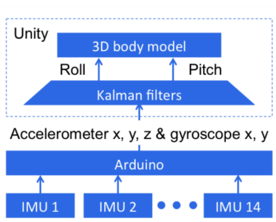
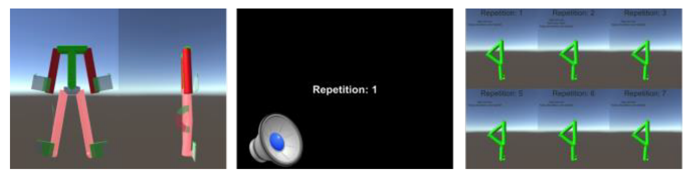


Figure 3: System Architecture for *Weight-Mate*.

In terms of implementation, the *Weight-Mate* suit used the FLORA wearable electronic platform (www.adafruit.com) and FLORA 9-DOF (accelerometer, gyroscope, magnetometer) sensors. The Arduino application was used to develop in C++ for the FLORA platform. The Unity game engine was used for processing the sensor data in C# and 3D rendered through a 3D constructed body using average body lengths from Plagenhoef et al. [12]. The system architecture is illustrated in Figure 3. Figure 4 illustrates how the system works. First, it has visual feedback on a screen in front of the weightlifter to help them with initial positioning of legs and arms (figure 4a). Second, it gives audio feedback for minor corrections to positioning during the lift (figure 4b), and finally it gives post-set visual playback of each repetition performed during the set (figure 4c).



(a) (b) (c)

Figure 4: Using *Weight-Mate*: (a) visual feedback on start position; (b) audio feedback during the lift; (c) post-set visual playback after the lift (c).

The initial design, focusing on leg movements, consisted of two IMU sensors tracking the weightlifter's calf and thigh, sewn into two pieces of cloth, for easy mounting on the weightlifter's legs. The sensors were connected to the Flora microcontroller, which was connected to the computer via USB (figure 5).

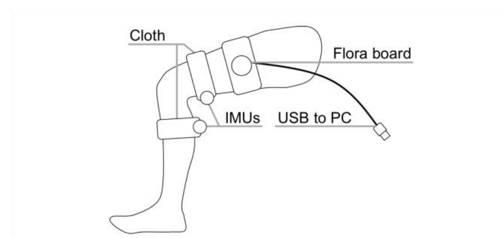


Figure 5: Initial prototype of leg wearables.

Foot, calf and thigh were constructed in Unity game engine using 3D cylinder objects, to bind the actual sensor data. We also colored the cylinder objects to indicate when the given body part was in a correct (green) or incorrect (red) position. The audio instruction given during the lift was downloaded using text-to-speech software [7] and implemented in Unity. We used a female voice, as research suggests it is perceived as more urgent, as feedback instructions given under pressure need to be [5].

4.2 First Iteration

The first iteration, started with a formative user evaluation of the initial design using the CUT method. This took place in a controlled environment using the setup illustrated in Figure 6. The participants were three experienced male weightlifters aged

23, 27, 29 with 2, 2, and 3-4 years of experience, respectively. Participants were introduced to the structure and tasks of the evaluation, including how *Weight-Mate* works.

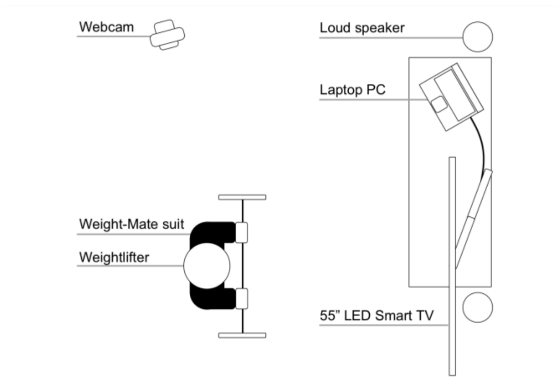


Figure 6: First iteration evaluation set-up.

To collect data, we used a webcam to record from the left side sagittal view (figure 7a), a laptop webcam to record from the front frontal view (figure 7b) and a copy of the user feedback screen (figure 7c). These images were combined using XSplit Broadcaster (figure 7). This combination view was used during the interpretation session between tester and participants after the interaction session. To ensure that weightlifters were physically pressured during their lifts, each participant had to perform three sets of 10 repetitions with 50 kilograms of weights. This gave the weightlifters a realistic experience of how it would be to wear the prototype in training. The weights were calculated based on the weightlifters' 1RM (One-Rep Max), which is the maximal weight a weightlifter can lift in a single repetition [4]. In the evaluation, we used weights 50% below the lifters 1RM to ensure they could focus on the *Weight-Mate* system.

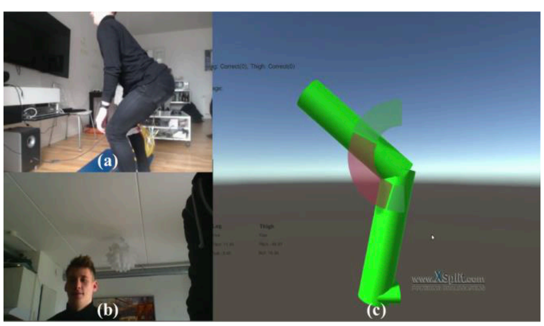


Figure 7: Combined evaluation views: (a) left side of lifter; (b) front view of lifter showing facial expression; and (c) feedback from system as see by test participant.

For the interaction session, the weightlifter stood in front of the large display showing body position feedback and completed the repetitions. They were not asked to think aloud, but to act as if this was a normal training session, to concentrate on the lift and respond to feedback given by the system. After the evaluation, in the interpretation session of CUT, we used retrospective think aloud protocol, as evaluators and the test weightlifter looked through the combination view of the session. This identified interaction problems with the system, the value of feedback given, what they were thinking at the time and how the system impacted their experience by asking when it guided them, and when it hindered them. They were also encouraged to give suggestions on changes and improvements to the design.

The evaluation revealed that audio instructions given during the deadlift were too immediate and therefore distracting. One weightlifter suggested that feedback instructions be given every third repetition. It was also mentioned that positive feedback at the end of the lift would be helpful, when repetitions were performed correctly. One lifter requested that system used Danish rather than English for audio feedback. We changed this for subsequent evaluations, as all test participants were Danish. Two of the weightlifters mentioned that they could not keep track of their repetitions because they were concentrating on listening to the feedback instructions. With respect to the post-set visual playback of the set at the end, one weightlifter suggested only showing incorrectly performed repetitions rather than all 10 reps of the set being played sequentially. The perceived usefulness of the feedback varied across the weightlifters. This may be because the implementation only delivered limited feedback on the lift, according to a fixed pitch motion of the calf and the thigh, and did not take into account the varying lengths of individual weightlifters' body parts.

4.3 Second Iteration

The second iteration involved both a refinement to the design of the prototype as well as a second formative evaluation.

4.3.1 Design Refinement. Based on the findings from the first formative evaluation, we decided to provide audio instructions only for each third repetition and an instruction indicating no errors at the end of each lift, if performed correctly. Furthermore, a visual repetition counter was added to the system display in order to help lifters keep track of them, incrementing each time a lift was completed. During the interpretation session, it was also noticed that the recorded video of the weightlifter from the side and the data gathered from the IMU and displayed on the system display revealed that the implementation with predefined fixed angles was not sufficient to measure correct movement to the fidelity required by lifters.

4.3.2 Implementation. Our first modification to the system was to add the remaining body parts involved in the deadlift to the system, including trunk, upper arms and forearms. Models were constructed in Unity with relevant audio feedback. In addition, audio instructions were changed to only play at the end of every third repetition, as suggested by test participants. With this increase in the number of sensors, the Arduino code needed to be optimized, increasing the frequency of collection of raw sensor data. To accommodate the provision of personalized feedback and make the system adapt to the specific weightlifter, the average length of body parts was calculated using the foot length and height of the weightlifter [12]. For this prototype version, these were inserted manually into the system. Ideally, the system would use sensor placement on body parts or image recognition software to automate this process.

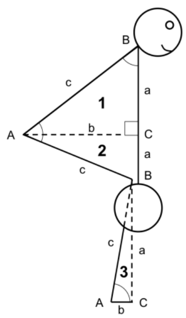


Figure 8: Weightlifter body divided into three triangles: 1, 2 and 3. A, B and C indicate angles, a, b and c indicate lengths.

Personalized feedback was then calculated using the cosine relations on the "triangles" of the body, 1, 2 and 3, as shown in Figure 8. The angle range for the leg was calculated by applying the cosine on angle 3A, 3b (length of foot) and 3c (length of calf). The angle range for the trunk was calculated using triangle 1 and 2, where angle 1B was calculated using 1A+2A, 1c (length of trunk) and 2c (length of thigh). Using the calculated angle 1B and 1A, 1C can be calculated. If the calculated angle was greater than 90° we determined that the shoulders were not over the barbell and the weightlifter's trunk need to be adjusted.

Figure 9: The *Weight-Mate* suit from (a) front and (b) back. The dotted circles indicate IMU locations.

The refined prototype consisted of 14 IMU sensors, one on each calf, thigh, shoulder, upper arm and forearm, and four along the trunk, as this body part is crucial to track during the deadlift. Since only one side of the body was needed to calculate the movement in the sagittal plane, we reduced the number of sensors, which. resulted having a sampling frequency of 12 Hz. The sensors were stitched into a compression shirt and a pair of compression tights, and the cables were covered with webbing (figure 9).

4.3.3 Evaluation. The evaluation setting for the second formative evaluation was the same as the first (see figure 6). The prototype was evaluated with three weightlifters aged 23, 27 and 27 all with 2 years deadlifting experience. Two had been involved in the first evaluation, and one was new. The task given to them was 3 sets of 10 repetitions using 50% of their 1RM, wearing the *Weight-Mate* suit. They were asked to focus on the lift during the interaction session, and informed we would subsequently hold an interpretation session where they would be asked to recall their experiences. The evaluation revealed that the *Weight-Mate* suit was comfortable to wear and did not hinder the weightlifters in performing the deadlift. It was also found that the start-calibration was not fully functional and not reliable. During the interpretation session, experienced weightlifters explained that they did not need the system to guide them into the starting position due to their level of expertise, and they were not concerned about being in the wrong start position. The weightlifters complemented the repetition counter as it made it easier for them to focus on the lift, while not distracting them from doing their own counting if they wished. We found that participants tended to pause every time the *Weight-Mate* system gave audio feedback; they explained this was because they wanted to focus on it in order to fully understand what was being said. Lastly, the post-set visual playback shown to lifters at the end of the set was reported as "overwhelming", because all repetitions were being shown at once with no clear indication of the mistakes made in each. Lifters also found it difficult to understand that each figure on the screen represented one repetition.

4.4 Third Iteration

The third iteration included a redesign based on feedback from the second iteration evaluation to produce the third prototype to evaluated with weightlifters with diverse of experience levels.

4.4.1 Design Refinement. Based on findings from the second formative evaluation, we decided to discard several parts of the system, including starting position instructions, all raw roll data, and sensor data from the shoulders. The final set of sensors used in the prototype included one on the left calf, one on the right thigh, four on the back and one on the left forearm. However, the sampling frequency of measurements was increased from 12 Hz to 36 Hz. Several feedback instructions were discarded as they were reported in the second evaluation as not necessary. At the same time, the post-set visual playback of the sets was redesigned such that each repetition was accompanied with a textual explanation and a repetition number (figure 10).

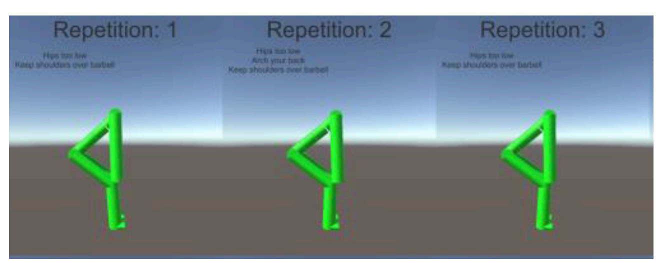


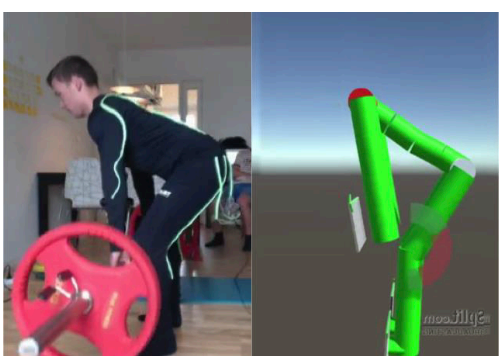
Figure 10: Post-set visual playback showing 3 of the set of ten repetitions with visual and textual feedback.

Furthermore, based on findings from the evaluation, we designed *Weight-Mate* to give immediate and personalized feedback regarding the weightlifter's trunk alignment, if it was not arched in the correct way, because it is critical to have the correct trunk position during the deadlift to avoid injuries. This redesign involved comparing the IMU logged data to the video recordings of the weightlifters, to ensure *Weight-Mate* was sensing this correctly, and that "Arch your back" feedback was given whenever the weightlifter's trunk was flexed.

	Sex	Age	Experience	Weights
W1	Male	23	2 years	40 kgs
W2	Male	25	4 years	100 kgs
W3	Male	29	3-4 years	90 kgs
W4	Male	27	2 years	70 kgs
W5	Male	18	1.5 years	70 kgs
W6	Male	27	2 years	40 kgs
W7	Male	21	2 years	70 kgs
W8	Male	25	2 years	70 kgs
W9	Male	22	2 years	70-120 kgs
W10	Female	23	1 years	40 kgs

Table 1: Experience and weights used by test lifters in the third formative evaluation.

4.4.2 Evaluation. Evaluation of the third prototype used similar setup as other phases (figure 6), but with 10 participants. We recruited an additional six weightlifters to evaluate the third prototype Weight-Mate. The tasks in this evaluation were designed to simulate a normal training session. As a result, test lifters were asked to choose how many kilograms of weights they wanted on the bar (see table 1). All ten chose to perform three sets of eight repetitions, as a standard training session for them. Their foot, shank, thigh and trunk measures were manually entered into the system.



(a) (b)

Figure 11: Using *Weight-Mate*: (a) performing the deadlift wearing the suit; (b) the body as rendered in Unity.

The CUT method was again used so that the interaction session allowed weightlifters to focus on the lift and feedback during the sets. Ten lifters performed their sets. Figure 11 shows one weightlifter deadlifting while wearing the *Weight-Mate* suit during evaluation (figure 11a), with Unity's rendering of his body movement (figure 11b). We discussed their experiences in interpretation sessions, after completing all 3 sets.

5 Findings

Using partial transcriptions of discussions with test lifters from the interpretation sessions of the third evaluation, and video tapes of the sessions, we conducted a thematic analysis [10] of their use of *Weight-Mate* during this simulated real training session. This involved coding the data, and creating categories in relation to codes, by grouping together different instances of related codes. Using this approach, we were able to group our findings about the usability and usefulness of the *Weight-Mate* system with respect to the adaptability of the system with respect to the individualized feedback provided to the test participants, how they felt wearing the suit, and how it supported their performance. Quotes in this section have been translated from Danish to English by the Danish authors.

5.1 Audio Feedback

The usefulness of the audio feedback was positively commented on by eight participants. However, W1 and W8 mentioned that they would need to get used to having audio feedback in order to completely adhere to it. We noted that W4 actually stopped doing their lift to listen to the audio feedback. Immediate corrective feedback that happened when a lifter's back was in the wrong position, was claimed be three participants to be very useful. However, those with less experience explained that it did not specify which direction the problem was in, that is, they did not know if their trunk was excessively flexed or excessively hyperextended, as the system did not indicate this. This level of instruction was not needed by the more experienced lifters.

Interestingly, this kind of immediate feedback was used differently by different participants. For example, W4 used it to correct his next repetition, while W7 tried to correct his position immediately. Four weightlifters commented on the *"Keep your shoulders over the barbell"* instruction, where two experienced lifters were positive about this instruction, while another two with less experience, explained they had difficulty in correcting their position from this audio instruction. This problem was partly exacerbated by the fact that the system did not always calculate the need for this feedback correctly, as the single suit used in the evaluations did not always fit participants snuggly. However, given the limited time and funds for this research, it was not practicable to build multiple suits of different sizes.

With respect to the distracting qualities of the audio, five of the lifters agreed that the audio feedback was not distracting during the lift. We noticed that in the first set, most participants stopped briefly to listen to the feedback, but after the initial experience of audio feedback, they continued their lifting while listening to subsequent feedback. From then on, they knew what to expect and how they would get feedback in the next set. However, W3 had problems with instructions playing simultaneously, and W5 had some problems hearing the feedback. W7 and W2 pointed out that the immediate *"Arch your back"* instruction could be a bit distracting during the lift. Additionally, W7 and W8 were annoyed by it because the instruction was sometimes not even correct, again, due to problems with a poorly fitting suit. As for starting position feedback, W10, the least experienced lifter, and W8 complained that it was frustrating and not helpful to get feedback at that point. This was an interesting contrast to information from a coach in our previous work, who said that novice lifters required the most instructions to adjust their starting position each lift.

Having positive audio feedback occurring after every third repetition, was judged by all participants to be appropriate. This feedback was claimed by eight participants to give them encouragement, and four wanted feedback that was even more positive. W8 reasoned that it would move the focus from just correcting the lift to including comments that would motivate the lifter to keep on pushing through the training, as this was an important role of the coach.

"If you then have performed three correct in a row then it (the instruction) could be extra positive" (W10)

However, W2, as the most experienced weightlifter of our participants mentioned that it was annoying to constantly be told that he was not lifting correctly, and W5, the youngest of our participants, did not find positive feedback necessary to his training.

The female voice chosen to give audio feedback, was found to be acceptable by most of the weightlifters. Five of them commented on it unprompted, and four thought it was fine when asked.

"It worked fine to have a female voice. The voice is very passive and very nice to have and is suitable if you don't think that the voice should take over the training" (W9)

As for the validity of our evaluation set up, W6 suggested that if he had used the system in a fitness center, were the audio feedback would need to be played through headphones, he would have had a more realistic experience of the system.

5.2 Visual Feedback

The post-set visual playback was reported by all weightlifters as a great feature. The playback enabled them to analyze their sets in a way that they were not able to do in their usual training, and they felt it definitely added value to being able to adapt their training focus during their deadlift. W6 added that in using *Weight-Mate* to look at the progression of the set, it became easier to identify when the technique started to fail due to their own physical fatigue.

"It's super cool to be able to see and analyze one's reps [...] it is nice to see where my mistakes are [...] from the side, there you can see all the points that are important when deadlifting" (W9)

The use of green and red color-coding for respectively correct and incorrect posture was easy to understand and helpful for the weightlifters to identify errors. However, in some repetitions the animation was red for such a small duration that the weightlifter did not register it, this especially happened with W10, the least experienced lifter.

5.3 Textual Feedback

The textual feedback helped weightlifters identify the mistakes in each repetition. It was praised for being short and precise, and helped weightlifters get a quick overview of mistakes made in a set, again helping them to adapt their own training focus. It also helped them to verify that the mistakes they saw in the animation, when it correlated with the textual feedback. However, W9, the lifter using the heaviest weights, did not notice the textual feedback, because he focused on the animation which was enough to get an understanding of what was correct and incorrect in the set, given his level of expertise. A concern raised by W10, the least experienced lifter, was that the text did not tell her how wrong she was and how to correct it, in the way a coach would have. She also added, that she would like to be able to see how critical her mistakes were.

"It could be cool if it highlighted (the mistakes) [...] so that I know which mistakes are more (critical), that way categorizing the mistakes (with highlights)" (W10)

The repetition counter, provided as text on the screen during the lift, when most feedback is audio, was found by five of the lifters to be very useful. They commented that it was a good way to keep track of their repetitions if they forgot to count and that the text on the screen did not distract them from the lift.

5.4 Combined Feedback Modes

The sequence of personalized audio and visual feedback was designed to help individual weightlifters in perfecting their deadlift, automatically adapting to their particular physical dimensions. It is therefore vital that the right kind of feedback is given at the right times in a way that is useful to the weightlifter. The right kind of feedback can support adaptation of training focus based on the lifters individual skill level. The combination of audio, visual and textual feedback in *Weight-Mate* was deemed to be useful by all participants.

"I think the basic idea and the way it is executed, I think that is the way it is supposed to be" (W4)

However, one recurring problem with the feedback was the dilemma of knowing how to correct some of the mistakes identified by *Weight-Mate*. W1 and W10, the two least experienced lifters, had trouble knowing how to correct their mistakes and also wanted to know to an exact degree how much they should correct their movement. For instance, when W10 got the feedback message *"Move your hips higher"*, she needed to know *"how much higher?"*.

5.5 The *Weight-Mate* suit

The wearability of the *Weight-Mate* suit was commented on by all participants. Nine agreed that it was comfortable to wear, but W2 found it too small. Also, W8 mentioned that he had to adjust his deadlift technique due to the tight fit of the suit. Since we were unable to custom make 10 suits within given time and resources, it ended up that for W1 and W10 the suit was too large, and for W2 and W9 the suit was too small. Additionally, W2 felt the suit was distracting, while W9 felt that it positively promoted muscle awareness.

The cables and sensors on the suit were commented on by eight participants who agreed that neither distracted them from performing the lift. Three participants commented that the suit was difficult to put on and off, and that the initial adjustment of the sensors was a bit annoying.

5.6 Lift Performance

The weightlifter's performance was a crucial part of the evaluation, as we wanted to verify that *Weight-Mate* helped our participants to adapt their deadlift technique appropriately. Noticeable and positive improvement in technique from their first or second set to their third was reported by five participants, and acknowledged that this was due to timely and useful feedback given by *Weight-Mate*. Furthermore, the data gathered from the IMUs in the suit supports this. The data indicates that the weightlifters were perfecting their deadlift and making less mistakes as they progressed through the sets. W10, the least experienced lifter, had several lifts in her third set, where she didn't make any mistakes.

"From the first to second set I felt a clear difference in my legs, maybe not so much from second to third set, as the problem there usually was the shoulders, but I could definitely feel a difference on where it affected [...] it was definitely much better, because it should affect the back and core and not so much the legs as you should not squat in the beginning" (W5)

In performing the deadlift to the best of their ability, none of the weightlifters mentioned being hindered by using *Weight-Mate*. In fact, W5 noted that there was virtually no difference between deadlifting in our evaluation while wearing the *Weight-Mate* suit, and deadlifting in his usual training clothes in the gym.

6 Discussion

Through the study of *Weight-Mate* in use, and through iterative design and formative evaluation refinements based on user feedback and suggestions, we were able to create a wearable assistive training system useful to all levels of weightlifters in correcting their technique. We also learned about those aspects and types of individual feedback that are required by lifters at different levels of expertise, and how an adaptive system could better assist lifters in perfecting their craft. Through audio, visual and textual feedback relevant to specific parts of the weightlifting activity with respect to available attention levels of the lifter, the *Weight-Mate* system helped our lifters to achieve an improved deadlift performance over several sets of repetitions. This improvement could be even further enhanced by levels of automated adaptive behavior of a system, designed to measure cognitive and physical capabilities of a user, and using AI and machine learning algorithms, adapt feedback to assist a specific individual.

6.1 Relevance of Feedback

Getting used to the different feedback modes of *Weight-Mate* happened fairly quickly for all participants. Each time a new audio instruction was given during a lift, the weightlifter took very little time processing the instruction and was able to focus on their lifting activity, and adapt their movements appropriately. The same was apparent in the post-set visual playback at the end of each set. After the first set, each weightlifter took some time to understand the eight figures representing each of the repetitions. After each of the following sets, they were able to immediately understand and benefit from the sequential visual representations of all eight repetitions, and how correct their positioning was in each one. They also easily understood the textual comments associated with each figure that explained what they did wrong during each rep and how to change to correct it. This played a vital role for the weightlifters in getting an understanding of how well they performed their entire sets and where their posture problems were. For the less experienced lifters, the level of incorrectness in the technique was missing from the feedback - an adaptive system would recognize the inexperience of the lifter, just as a coach would - and provide the additional detail required.

Having input from lifters during the design process helped to shape the feedback so that the different types of feedback used were appropriate to different parts of the lift, and supported them during the high stress parts of the activity. Their input on changing the audio feedback to their native language and having a real voice rather than the initial computer generated English voice added to the ability of the instructions to blend into the weightlifting activity.

6.2 Impact of Adaptability

The ability of the system to adapt to the bodily dimensions of the individual was an important aspect of the system. The design of the suit was in a flexible fabric that enabled it to adapt to several body sizes in the one suit, but having a small, medium and large version of the suit would have been preferable. Although our longer-term design intention is to provide automated adjustment in terms of physical and cognitive capabilities of the lifter, and feedback appropriate to their expertise level, the feedback currently provided was generally sufficient for each lifter to adapt their own positioning and training focus, such that they were already able to improve their lift technique over the 3 set trial in the third evaluation.

6.3 Wearability of the suit

The design of the *Weight-Mate* suit was well accepted by lifters. Apart from a couple of lifters who were either too small or too large for the suit, they found it comfortable to wear, and it did not adversely affect their lifting technique. In fact, they all reported that wearing the suit and getting feedback from the system, made their training session more fun and motivating than doing it by themselves. We did, however, find technical limitations with the prototype suit. Each sensor requires four wires from the sensor to the FLORA board, which meant that the shirt of the suit had 32 wires running down the back. This lead to some unforeseen problems. When weightlifters bend their backs some sensors would be put under strain, or even become disconnected. Furthermore, it also meant that we could not hide the FLORA mainboard in a pocket inside the suit without compromising the data from the bottom sensor on the back.

6.4 Improved Deadlift Performance

All weightlifters reported that they felt their personal performance of the deadlift had improved through using *Weight-Mate*. They also felt that they quickly grew accustomed to receiving feedback while deadlifting, and that they could immediately make use of that feedback to adapt their position and improve their lift. We could see from the data, that there was a noticeable improvement in correcting their technique from the first set to the last set in the third evaluation, but this could be a result of them warming up, and we did not measure and compare if this was a usual occurrence during training sessions. However, even if this is generally the case during training, *Weight-Mate* would always serve a useful purpose during initial sets, because if the weightlifter is still warming up, this is when doing the deadlift with the correct technique becomes even more crucial to avoid injuries.

6.5 Technical Limitations and Future Work

The FLORA IMU sensors with the Kalman filter showed that it is possible to precisely capture the movement in the sagittal plane of the conventional deadlift using the pitch data only. One limitation to *Weight-Mate* is that we were unable to capture subtle problems with positioning in the frontal plane, such as lifting crookedly while extending to an upright position or flexing into a downward position. This was in our initial design for *Weight-Mate*, but due to hardware and implementation difficulty, and time constraints we disabled this feature in order to focus on core components of the system in the sagittal plane. Future implementations of *Weight-Mate* should add roll data into the feedback calculation.

The number of sensors enabled in the final prototype was much lower than previous versions. This was because the FLORA platform was not able to transmit data at the desired frequency to support the Kalman filter, the more sensors that were enabled the lower frequency it produced, which meant that we had to disable sensors in order to achieve a desirable frequency. This was a limitation of the FLORA platform that we did not encounter until late in the development cycle. Even so, with 14 sensors enabled on the FLORA platform, we did not have a surplus of electrical power to support a Bluetooth module to make the *Weight-Mate* system wireless.

In future development, to get finer granularity feedback and to make the suit wireless, we would have to find a more powerful platform, capable of adding sensors and transmitting data higher frequencies. We would then continue working in iterations, with continued close involvement of weightlifters. We would like to test the use of the system in a real gym, with extra users, which would likely highlight problems that we did not find in the controlled environment. We would also like to develop further the design implications that surfaced during the evaluations for supporting the need for AI based adaptive system that provided individualized feedback for lifters based on their experience needs.

7 Conclusion

This paper addressed the concept of adaptive digital training support for weightlifting through studying the iterative development of a wearable assistive computer system, *Weight-Mate*. It was designed and implemented iteratively using the cooperative usability testing (CUT) method involving weightlifters in the design and evaluation processes.

The system works in conjunction with sensory feedback to assist all levels of weightlifters in adapting their technique for the conventional deadlift. The *Weight-Mate* suit captures the orientation of the weightlifter's body parts and uses the lifters physical dimensions compared with a model of an ideal lift to calculate misalignments. The system then gives appropriate, non-intrusive and timely feedback to the weightlifter, both during and after performing the deadlift. This information assists weightlifter's enhanced training and supports them in adapting their body positioning both during the lift, and after the lift, providing visual feedback supporting reflection on performance.

This study contributes to HCI by showing how the involvement of weightlifters and coaches during the iterative development of a wearable training prototype can surface design requirements for individualized and appropriate feedback in a situation where the user is under immense physical and psychological pressure. It also highlights the training information needs of weightlifters at different levels of expertise, to inform the design of an adaptive digital training system for weightlifters.

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