Weight-Mate: Wearable System for Perfecting the Conventional Deadlift

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ABSTRACT
Weightlifting is easy to learn, but hard to master. People who do weightlifting do it to improve their health, strengthen their muscles and increasingly build their physique. However, due to the complex and precise body positioning required, even experienced weightlifters need assistance in getting the deadlift technique correct.

In this paper, we present Weight-Mate, a wearable prototype system for experienced weightlifters. Weight-Mate provides audio and visual feedback to weightlifters so they can precisely track their own body movements in a way that is seamless and non-distracting, while supporting them in their goal of completing a deadlift with correct technique.

Weight-Mate was iteratively developed through a series of user-centred formative evaluations of studying the system in use with experienced weightlifters. Based on user feedback and our observations, we have improved the design of the sensor suit required to map current body locations in the deadlift. We have also identified the kind of digital feedback, both audio and visual support, which can assist weightlifters in correcting their deadlift technique during training sessions. A summative evaluation with 10 weightlifters showed that our improved design of the Weight-Mate prototype system helped them to achieve an improved deadlift performance, while using the system to perform their usual training regime.

Author Keywords
Body motion analysis; Body Area Network (BAN); weightlifting; deadlift; IMU; fusion algorithm; Kalman filter; audio feedback; visual feedback; real-time user feedback; 3D movement; motion capture; motion sensing; on-body sensors; wearables

ACM Classification Keywords
H.5.2 Information Interfaces and Presentation (e.g. HCI): User Interfaces; I.4.8 Image Processing and Computer Vision: Scene Analysis;

INTRODUCTION
Weightlifting improves health and strengthens the body muscles, but the technique of a weightlifting exercise is of the utmost importance in order to obtain the full efficacy of the exercise and to improve performance. Because the exercise enables several joints, the deadlift exercise demands excessive concentration by the lifter, to build competence and avoid injuries. At the same time, 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, so as to not break the lifter's intense concentration toward completing a correct and safe deadlift.

Experienced weightlifters provide an interesting case in the development of assistive training technology because they are pushing their physical capabilities to their limit and beyond. They do the deadlift under such immense physical and psychological pressure, that sometimes their concentration and stress levels are so intense that they have been known to actually pass out - A potentially harmful situation if they are lifting heavy weights. At the same time, people in these high concentration situations can benefit from training information about the correctness of their posture to help them make physical adjustments that positively impact their performance.

There is an opportunity in weightlifting support to design a system that can track the body movements during the deadlift and provide subtle, but useful, feedback without distracting the weightlifter.

In our research, we address the following question:

How can wearable technology in conjunction with sensory feedback assist experienced weightlifters in perfecting the conventional deadlift?

RELATED WORK
There are very few research studies in the area of wearables and other emerging technologies being designed to assist in weightlifting. However, there are several studies using these technologies to support other physical activities such as exercising, martial arts, and physiotherapy. In this section, we will present research in these related areas, as well as a study on weightlifting, to compare the different technologies and ways of providing feedback during the exercise, with the purpose of designing and implementing a system specifically for weightlifting support.

Camera Tracking

Within body tracking one prominent technology is to track users using a depth motion camera, such as Microsoft Kinect. Substantial research has been made to highlight how the camera can be used to track users' movement and body position. Anderson et al. propose YouMove, which is a system that enables the user to record and learn sequences of body movement using a Microsoft Kinect camera. The user is guided through a mirror that augments the user with an overlay of a stick figure showing the movements to be learned. Through 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 an improvement of 44% of the movement, compared to a video demonstration of the same movement, which was only 20%. In addition, YouMove had a greater retention rate than the video demonstration. However, the YouMove system suffered from tracking particular body movements when moving towards the camera. The YouMove implementation also demanded a large mirror in front of the user, making it inflexible to move to other locations [2].

This indicates that an interesting way of providing feedback to users is through augmentation. Computer-generated graphics that overlays a real-time camera feed of the user to enhance the immediate feedback for the user is an example of augmentation. Tang et al. propose Physio@Home, which allows the user to perform physiotherapy exercises at home through two Kinect cameras; one tracking in front and one tracking from the top of the user. The user is given feedback by a screen showing the picture from each camera augmented with designed feedback arcs, which guide the user in the correct positioning of limbs in the exercise. Tang et al. deduced from a user study that the designed feedback arcs combined with multiple views was the most accurate guidance. Yet the Physio@Home implementation demanded two cameras and was sometimes subject to the camera markers not being visible for the camera, which created instability in the tracking of the body [11].

While cameras can accurately track movements, the accuracy does get penalized when the user stands in certain positions or if obstacles are in the way. Velloso et al. propose MotionMA, which enables the user, in a similar way to YouMove to record and learn arbitrary body movement sequences, but instead of relying solely on a Kinect camera MotionMA also utilizes on-body sensors measuring the orientation of upper and lower arm. The record and learn interface of MotionMA was positively received by the weightlifters in respect to the accuracy of the demonstrated movement. Even so, the MotionMA system was still limited in its ability to tell whether the hand was opened or closed and hand and feet were not tracked accurately enough. Furthermore if the user was facing the camera with limbs pointed to the camera, the camera could not track the movement [12].

On-body Sensor Tracking

Using on-body sensors to detect and recognize movement patterns has been a basis for multiple studies. This technology has proven to be reliably used as a technology for recognizing full body movement patterns. Kowsar et al. propose a system, which can detect unseen anomalies in weight training exercises based on a dataset containing 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 their system could detect unseen anomalies in weightlifting using only the accelerometer with 98% accuracy showing the potential of IMUs. They also showed the potential of only processing one movement axis of data during the weightlifting exercise, which encourages us to look at whether the deadlift can be processed with one movement axis as well [7].

An advantage of on-body sensors is that a screen is not always necessary in order to provide feedback. Ananthanarayan et al. propose PT Viz, a system for knee rehabilitation exercises. The user is equipped with a knee wearable worn around the thigh and calf. The wearable sleeve on the thigh contains a sensory display with green light strips indicating the range of motion of the knee. Positive reactions from users were acquired in regard to the wearability and portability of PT Viz. One user even suggested that more light strips would be an improvement, in order to identify more subtle improvements of the exercises [1].

Feedback Under Pressure

In HCI literature, there are several studies about people who are interacting with technology in mentally stressful situations, e.g. air traffic control [3]. However, we have not found research about receiving or providing feedback under physical pressure. Research in other research areas, such as social and behavioural science, show how different types of feedback can help participants to lower their stress level during a mentally stressful scenario. Zuiderduin proposes a system, Cognitive Feedback System (CFSystem), to help people make good decisions in stressful situations. The research group made a naval simulation, where participants were asked to put out fires according to the urgency of the fire and people without any fire-fighting or naval experience could perform the simulation. They found that by providing three feedback types, biofeedback in the form of a heart rate monitor, a performance prediction and an error prediction, they were able to significantly increase the performance of their weightlifters, compared to giving no feedback [13]. This is interesting for Weight-Mate because there is much information and feedback that could be provided by Weight-Mate. However, it is speculated that getting too much feedback under pressure may hinder the weightlifter in using the feedback given, because subtle movement requires intense concentration while lifting under heavy weight load. Furthermore, we must ensure that the feedback provided by

Weight-Mate is useful and does not break the weightlifter's concentration.

ANATOMY OF THE LIFT

In this section, general body anatomy is briefly described along with a description of the physical attributes of the deadlift.

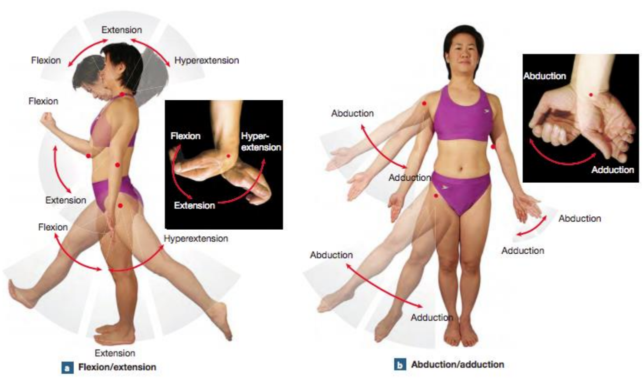
Body Anatomy

In order to describe and understand the deadlift exercise certain prior knowledge is introduced about the anatomy of the human body and its movements.

As seen in Figure 2, the body can be divided into: frontal plane (blue plane) dividing the body into back and front; sagittal plane (red plane) dividing the body with a so called *midsagittal line* into left and right; and the transverse plane (green plane) dividing the body into upper and lower body [8].

In addition the body can be divided into head, neck, upper limbs comprising the body parts from shoulder to hand, lower limbs comprising the body parts from hip to foot, trunk comprising the back, chest, abdominal, loin and pelvis [8].

The body is capable of angular, rotational and special movements. Because angular movements are the most prevalent in deadlift, these are described and are illustrated in Figure 1. The first angular movement is *flexion* (Figure 1a), which occurs in the sagittal plane by decreasing the angle between the body parts in action. The counterpart to *flexion* is *extension*, which in contrast is increasing the angle between the body parts in action. The other angular movement is *adduction* (Figure 1b) which occurs in the frontal plane by decreasing the angle between the given body part and the midsagittal line. The counterpart to *adduction* is *abduction*, which in contrast is increasing the angle between the given body part and the midsagittal line [8].



(a) (b)

Figure 1. Angular movements comprising (a) flexion/extension and (b) abduction/adduction [8].

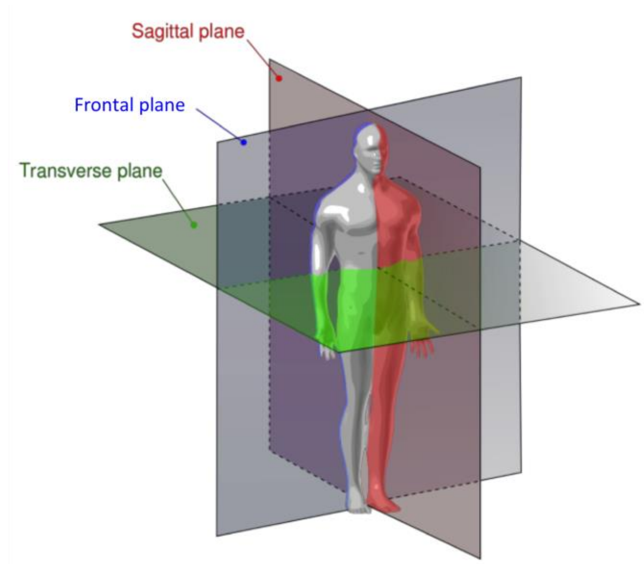


Figure 2. The human body divided into frontal, sagittal and transversal plane [8].

The Deadlift Exercise

The deadlift exercise proceeds by starting with flexed thighs and calf with shoulders aligning with the barbell (Figure 3a). The weightlifter then lifts the barbell by extending the thighs and calves to get in a raised position (Figure 3b). The muscles engaged in this compound weightlifting exercise are thigh, hips, buttock and loin (Figure 3c). The deadlift exercise was chosen, because it is one of the exercises that engages the most joints and it is a safer exercise as the weightlifter simply can let the barbell go when reaching failure, without getting hurt [10].

(a) (b) (c)

Figure 3. Performing the deadlift, where (a) is the start position with arrows indicating how to move the body to end in the end position (b). The upright position of the deadlift (c) illustrates the muscles engaged.

STUDY DESIGN

To study how to provide feedback under physical pressure we developed *Weight-Mate*. Weight-Mate is a system consisting of the Unity game engine and a compression suit with sensors aligned on legs, trunk, shoulders, and arms using the FLORA wearable electronic platform. We designed the study of Weight-Mate in four phases: *Phase 1: Initial Design, Phase 2: First Iteration, Phase 3: Second Iteration,* and *Phase 4: Final Prototype.*

During Phase 1, the initial design of Weight-Mate, we investigated the wearable technology and Unity and how it could be used to develop a computer system for providing feedback to a weightlifter performing the deadlift exercise, and applied this to the basic design from our previous study [10].

In Phase 2, the goal of the first iteration was to take the initial prototype, designed to focus on the lower limbs of the weightlifter and evaluate how the technology was working in a limited area of the body. The prototype was evaluated with three participants in a formative evaluation, where the participants were evaluating the prototype by performing the deadlift exercise with weights.

In Phase 3, the goal of the second iteration was to refine the prototype based on the weightlifter's feedback from the first iteration and expand the prototype by implementing sensors for all body parts. We expanded the prototype in Unity to simulate the weightlifter's body and developed a new prototype suit that would carry all the sensors needed to simulate a weightlifter's body. The prototype was evaluated with three weightlifters in a formative evaluation, where the weightlifter was deadlifting with weights to study how they reacted to feedback under pressure.

In Phase 4, Weight-Mate was refined based on the results of the second formative user study, producing a final prototype that was a result of all the refinement during the iterations. The final prototype was evaluated in a summative evaluation with 10 weightlifters performing the deadlift exercise with their maximum lifting weight.

PHASE 1: INITIAL DESIGN

In a prior study, we designed three prototypes based on interviews with three weightlifters, a physiotherapist and a coach in order to evaluate different kinds of feedback, which the weightlifter should use throughout the deadlift exercise. These prototypes were then evaluated using a Wizard-of-Oz approach to simulate different technology options, with six weightlifters. As part of our findings, we discovered that the optimal feedback was providing visual feedback which the weightlifter should use to adjust their start positioning. Once the weightlifter started lifting, the weightlifter would receive audio instructions during the lift. When the set was completed a visual feedback would be provided, showing the different repetitions of the set [10].

Based on our previous results, and findings from related work, we chose to use IMUs for tracking the body movements in our implementation of an initial prototype for this study. We did this instead of using cameras due to limitations in cameras, including correct light settings and the inconvenience to bring along a camera to each weight training session, as well as lifting weights getting in the way of the viewing angle of the camera, rendering the camera obsolete.

We tested the performance of different fusion filters, including the Madgwick MARG, Mahony and Kalman filters and ended up implementing Kalman filters as they provided the most precise and responsive motion data. During this testing, we also identified that only the roll motion (in the frontal plane) and pitch motion (in the sagittal plane) were needed during the deadlift and this aided the implementation immensely because yaw motion (in the transverse plane) was inaccurate with our setup. Our developer testing of the system showed that it was sufficient to use roll motion for start positioning and pitch during the exercise, as used by Kowsar et al. with the axis of effect idea [7].

In our initial prototype, Weight-Mate was implemented using the FLORA wearable electronic platform and FLORA 9-DOF (accelerometer, gyroscope, magnetometer) sensors. Furthermore, the Arduino application was used to develop the electronic platform in C++ for the FLORA platform. Lastly, the game engine Unity was used for processing the sensor data in C# and 3D rendered through a 3D constructed body using average body lengths from [9]. The system architecture is illustrated in Figure 4.

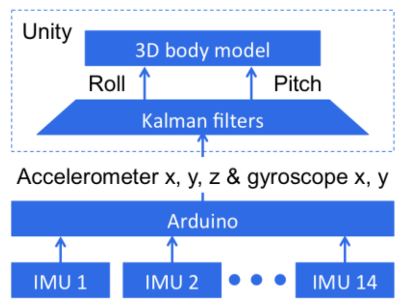
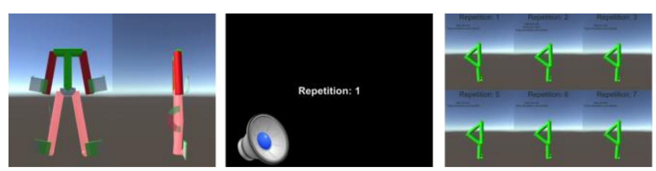


Figure 4. System architecture for Weight-Mate.

As seen in Figure 5 the weightlifter operates the system by letting the weightlifter (Figure 5a) position the legs and arms in the correct start position. Then during the set of lifts (Figure 5b) the weightlifter is provided with audio feedback. After the set (Figure 5c) the weightlifter can review a retrospective playback, which simulates each of the repetitions that were performed on the screen.



(a) Start positioning **(b) Performing the deadlift** **(c) After the set of deadlifts**

Figure 5. Use pattern of Weight-Mate. The weightlifter starts by positioning into the start position (a). Then when performing the deadlift, the weightlifter is provided with audio feedback instructions (b). After the set of deadlifts, the weightlifter is provided with a retrospective playback of the different repetitions of the set (c).

PHASE 2: FIRST ITERATION

Phase 2 focused on a formative user evaluation of the initial prototype. The Phase 2 prototype consisted of two IMU sensors to track the weightlifter's calf and thigh. The sensors were sewn into two pieces of cloth, for easy mounting and dismounting on the weightlifters. The sensors were connected to the Flora microcontroller, which was connected to the computer via USB (Figure 6).

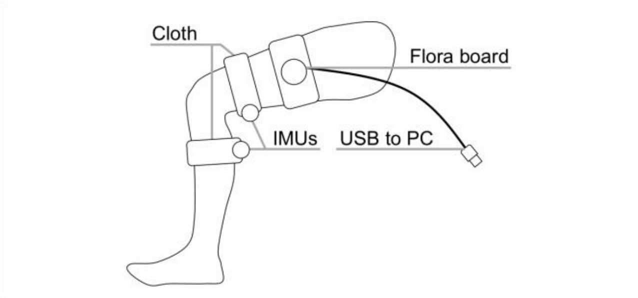


Figure 6. Illustration of prototype for Phase 2.

In Unity a foot, calf and thigh were constructed using 3D cylinder objects, which were used to bind to the actual sensor data. We also decided to colour the cylinder objects red or green when the given body part was in an incorrect or a correct position, respectively. In addition the audio instruction to be used during the lift was downloaded from the online text-to-speech software [6] and implemented in Unity. We decided to implement a female voice because it is perceived to be more urgent as the feedback instructions indeed are [5].

Formative Evaluation 1

The evaluation of Weight-Mate in Phase 2, took place in a controlled environment with three experienced male weightlifters aged 23, 27, 29 with 2, 2, 3-4 years of experience, respectively, using the setup illustrated in Figure 7. The weightlifters were introduced to the structure of the evaluation, including how Weight-Mate works, their lifting task and the semi-structured interview. The evaluation started with the weightlifter standing in front of a screen, with webcam recording from the left side (Figure 8a), a built-in webcam recording from front (Figure 8b) and a screen recording of Weight-Mate on the computer (Figure 8c). Figure 8 shows the total screen recorded with XSplit Broadcaster and shown to the weightlifter in the semi-structured interview. To ensure that the weightlifters were physically pressured during their lifts, each participant had to perform three sets of 10 repetitions with 50 kilograms of weights. The weights helped the weightlifters get a more realistic experience of how it would be to wear the suit in a deadlifting set. The weights were calculated based on the weightlifters' 1RM (One-Rep Max). 1RM is how much a weightlifter can lift in a single rep [4]. We used a 1RM calculator and aimed for a 1RM below 50% to ensure that weightlifters could focus on the Weight-Mate system.

The task given to the lifters was to use Weight-Mate without thinking aloud in order to fully concentrate on the lift and the feedback given by the system. The weightlifter was asked to adjust in a deadlift starting position before using Weight-Mate.

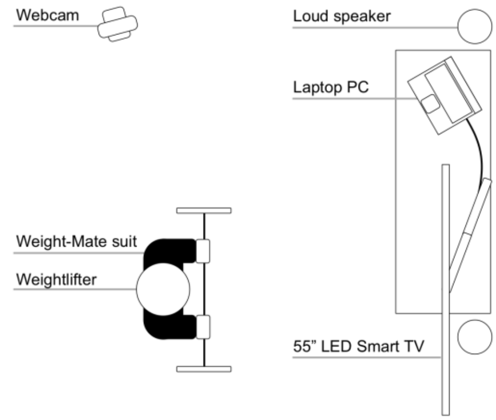


Figure 7. Evaluation Setup

After the evaluation, we used the retrospective think aloud protocol as we looked through the video with the weightlifters and asked what they were thinking at the time while performing the lift 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 prototype design.

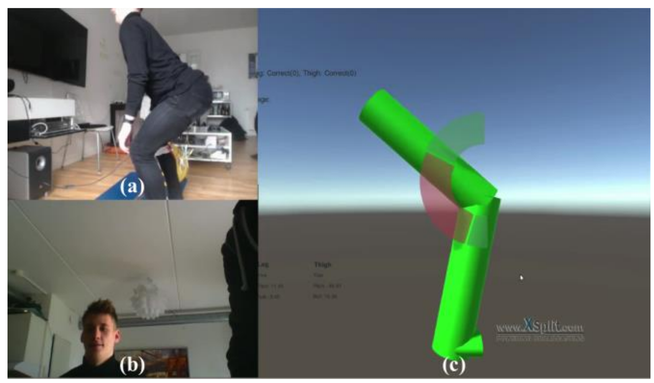


Figure 8. Weightlifter using Weight-Mate during evaluation, where (a) is the perspective from the webcam used to capture the moving body parts during the lift, (b) is the perspective from the front camera from the PC, used to indicate the degree of exertion via the facial expression and (c) is Unity rendering IMU data from the weightlifter.

The evaluation revealed that the audio instructions during the deadlift were too immediate and therefore distracting. One weightlifter suggested that the feedback instructions could be played every third repetition. In addition, it was mentioned that positive feedback at the end of the lift would be helpful, when the repetitions were performed correctly. Furthermore, two of the weightlifters mentioned that they could not keep track of their repetitions because they concentrated on listening to the feedback instructions. With respect to the retrospective playback after the lift, one weightlifter suggested only playing the wrongly performed repetitions instead of all being played sequentially. The perceived usefulness of the feedback varied across the weightlifters because the implementation at that time only calculated the feedback according to a fixed pitch motion for both the calf and the thigh, which meant that it did not take into account the varying lengths of the weightlifters' body parts.

PHASE 3: SECOND ITERATION

Phase 3 involved both a refinement to the design of the prototype as well as a formative evaluation of that redesign.

Design Refinement 1

Based on the findings in the first formative user study, we decided to provide a set of suitable audio instructions for each third repetition and an instruction indicating no errors at the end of the lift, if the weightlifter performed the deadlift correctly. Furthermore, a visual repetition counter was added in order to keep track of the number of repetitions. This repetition counter was shown on the screen in front of the weightlifter and would increment each time a weightlifter completed a lift. Comparing the recorded video of the weightlifter performing the deadlift and the data gathered from the IMU revealed that the implementation with predefined fixed angles measuring correct from wrong movement did not suffice. Therefore, we decided to take the lengths of the body parts into account in order to fine-tune the feedback to each weightlifter.

Implementation

Similar to Phase 1 the remaining body parts, including trunk, upper arms and forearms, were constructed in Unity and suitable audio instructions for the feedback were added. In addition, audio instructions were changed to play at the end of every third repetition as one of the weightlifters had suggested.

Due to the large amount of sensors to be processed the Arduino code was optimised, which increased the frequency for the raw sensor data.

To accommodate the fine-tuning of the feedback according to the specific weightlifter average length of body parts according to [9] were calculated using the foot length and height of the weightlifter. The length of the foot and the height of the weightlifter were inserted manually into the system. The fine-tuned feedback was then calculated using the cosine relations on the triangles the body resembles, triangle 1, 2 and 3 seen in Figure 9. The angle range for the leg was calculated applying cosine on 3A, 3b (length of foot) and 3c (length of calf). The angle range for the trunk was calculated using triangle 1 and 2 in the following way. Firstly, 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 and if this angle turns out to be more than 90° we can tell that the shoulders are not over the barbell and the weightlifter's trunk is hereby in a wrong angle.

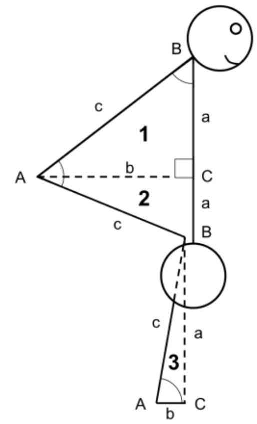


Figure 9. Body divided into three triangles: 1, 2 and 3. A, B and C indicate angles while a, b and c indicate lengths.

The Phase 3 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 resulting in a frequency of 12 Hz. The sensors were sewn into a compression shirt and a pair of compression tights, where the cables were covered with webbing.

Figure 10. The Weight-Mate suit from front and back. The circles with dotted lines indicate where the IMUs are sewn into the suit.

Formative Evaluation 2

The evaluation setting for the second formative evaluation was the same setting as the first evaluation. The prototype was evaluated with three weightlifters aged 23, 27 and 27 all with 2 years deadlifting experience, but with one new weightlifter replaced in relation to formative evaluation 1. The task given to the weightlifter was to evaluate the Weight-Mate system consisting of both the suit and the software with 50% of their 1RM. Again, the weightlifters were asked to focus on the lift during the evaluation, as we would use retrospective think aloud protocol with them subsequently, while viewing videos of their lifts and asking them to recall their experiences.

The evaluation revealed that the Weight-Mate suit was comfortable to wear and it did not hinder the weightlifters in performing the deadlift. The evaluation showed that the start-calibration was not fully functional and not reliable, and furthermore during the semi-structured interview the experienced weightlifters said that they did not need the system to guide them into the starting position, they were not worried 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 being distracted by their own counting or the counter on the screen. Each weightlifter would stop every time the Weight-Mate system gave them audio feedback; this was a result of wanting to focus their hearing on the feedback and to fully understand what they were being told. Lastly, the retrospective playback, after the lifts had been completed, was overwhelming and not easy to understand. They did not understand that each figure on the screen represented one repetition and it was overwhelming that all the lifts were being showed at once with no clear indication of the mistakes made in each repetition.

PHASE 4: FINAL PROTOTYPE

Phase 4 involved a redesign of the prototype based on the second formative user evaluation, and we also conducted a summative evaluation of the system with additional weightlifters.

Design Refinement 2

Based on the findings from the second formative evaluation, we decided to discard several parts of the system, including the start positioning, all raw roll data, and sensor data in the shoulders. The sensors remaining were one on the left calf, one on the right thigh, four on the back and one on the left forearm. Several feedback instructions were thus discarded as they were seen as secondary in respect to the current instructions. However the frequency increased from 12 Hz to 36 Hz. At the same time the retrospective playback of the sets was redesigned and each repetition was accompanied with a textual feedback instruction and a repetition number seen in Figure 11.

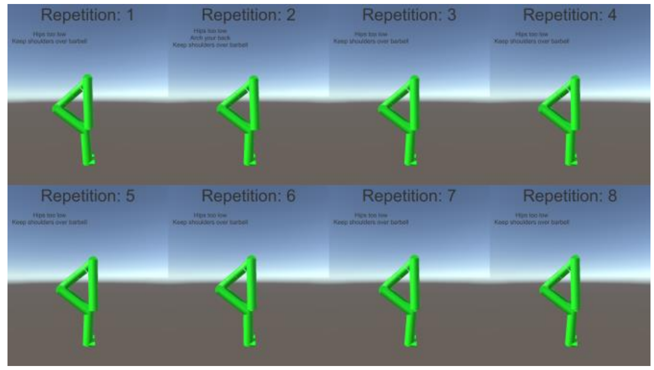


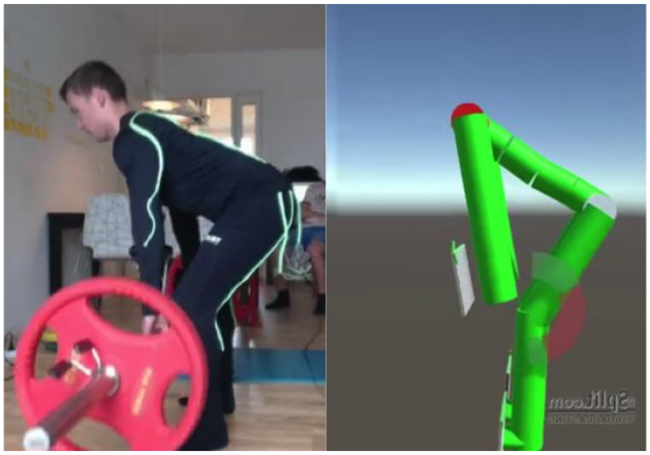
Figure 11. Retrospective playback with a set of eight repetitions with textual feedback.

Furthermore, based on the findings of the formative evaluation we decided to enable Weight-Mate to play feedback instructions regarding the weightlifter's back immediately when the back is not arched in the correct way, because it is a critical measure during the deadlift as it can cause back injuries.

IMU data logged during the lift was compared to the video recording of the weightlifter, so that the way in which Weight-Mate evaluates could be tested for correctness, i.e. whether the "Arch your back instruction" was instructed whenever the weightlifter's back in reality was flexed or hyperextended.

Summative Evaluation

The setting for the summative evaluation was the same as the first and second formative evaluations. We recruited more weightlifters to get more data about the use of Weight-Mate. We ended up evaluating the system on 10 weightlifters, where six had never tried the system before. During which time, we would fix small bugs or implement small feedback suggestions that did not change the system in a major way. The purpose of the summative evaluation was to evaluate the system on weightlifters, where they would perform the deadlift as if it was a normal training session. That means that the weightlifters were in charge of how many kilograms they wanted on the bar and all weightlifters chose three sets of eight repetitions (see Table 1). Figure 12 shows a weightlifter deadlifting and Unity's rendering his body movement. The retrospective protocol was used again to let the weightlifters focus on the lift while performing it and all the feedback they had about the system would be discussed in the interview afterwards. Furthermore the weightlifter's foot, calf, thigh and trunk were measured and manually inputted to the system.



(a) **(b)**

Figure 12. Performing the lift with Weight-Mate, where (a) is the weightlifter performing the deadlift wearing the Weight-Mate suit and where (b) is the weightlifter's body rendered in Unity.

	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. Data on the weightlifters W1-W10, including weights used in summative evaluation.

FINDINGS

Based on the semi-structured interviews from the evaluation, particular aspects of interest about Weight-Mate were identified in the collected data through a modified thematic analysis, the same as used in our previous study [8]. Using this approach, we had more time to evaluate more weightlifters using Weight-Mate, hereby generating more data that needed to be analysed. We argue that this approach is better suited for evaluating Weight-Mate, because we are more interested in evaluating multiple weightlifters, as this allows us to showcase a broader picture of the Weight-Mate system's feedback and usefulness.

The Weight-Mate Suit

All weightlifters commented on the feeling of wearing the suit and nine agreed that it was comfortable to wear, whereas W2 felt that it was too small. However, W8 mentioned that his deadlift technique had to be adjusted and grown accustomed to due to the tight fit of the suit. With respect to the fit of the suit, W1 and W10 commented that the suit was too large whereas W2 and W9 commented that the suit was too small, where W2 felt it was distracting and W9 felt that it promoted muscle awareness.

Eight weightlifters commented on the cables or sensors on the suit and all agreed that neither the cables nor the sensors distracted them from performing the lift. Three weightlifters commented that the suit was difficult to put on and off whereas W4 pointed that the initial adjustment of the sensors was a bit annoying.

Audio Feedback

With respect to the chosen voice to give audio feedback, five weightlifters commented on the voice and four thought that the voice was fine.

"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*

However, W3 requested the language used be his native language, Danish. Since he was the first weightlifter evaluated, we decided to implement Danish-speaking audio feedback for the subsequent evaluations, as all weightlifters were Danish.

Eight weightlifters commented on the audio feedback during the lift. W1 and W8 mentioned that they would need to get accustomed to the audio feedback in order to completely adhere to it. There was one episode in which W4 stopped the lift and listened to the audio instructions. In addition, W4 focused on the feedback given in the upcoming set whereas W7 tried to correct it immediately.

Five weightlifters asserted that the feedback was not distracting during the lift. However, W7 pointed out that the immediate "Arch your back" instruction could be a bit distracting.

In relation to the disadvantages during the lift, W2 mentioned that it was annoying to constantly be told that he was not lifting correctly. W5 had some problems hearing the feedback. W6 reflected upon the experimental scenario, which he felt influenced the experience of Weight-Mate and suggested that if he used the system in a fitness centre with audio being played through headphones, he would have a more realistic experience of the system.

With respect to the positive instructions given by the system, five weightlifters commented on positive instructions, where four desired more positive instructions. W8 reasons that it will move the focus from only being on the bad things to also include the good things.

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

However, W5 did not find positive feedback necessary to his lift.

Six weightlifters commented on the frequency of the instructions, where all replied that it worked fine getting the feedback for each third repetition. However, W3 experienced the "Arch your back" and the other instructions playing simultaneously, which frustrated him.

Five weightlifters commented on "Arch your back" instruction, where three weightlifters thought it worked fine with the instruction playing immediately when you bend your back. However, three weightlifters missed knowing which direction the incorrect back motion, i.e. too flexed or hyperextended as this was not included in the feedback. Disadvantages according to the "Arch your back" instruction were raised by W10 and W8 pointing out that it was frustrating getting the instruction when in the start position. In addition, W2 mentioned that it was a bit distracting during the lift whereas W7 and W8 were annoyed because the instruction did not reflect reality because of the misfit of the suit.

Four weightlifters commented on the "Keep your shoulders over the barbell" instruction, where two weightlifters were positive about this instruction in contrast to the remaining two weightlifters that had a hard time correcting according to this instructing. However, the implementation of this instruction did not always reflect reality, which made it hard for the weightlifters to act on the instruction.

There were no weightlifters that triggered the "Don't let your knees exceed your toes" instruction.

Visual Feedback

Every weightlifter that evaluated Weight-Mate thought that the retrospective playback was a great feature of Weight-Mate. The retrospective playback enabled them to analyse their sets in a way that they were not used to, which added value to their deadlift training. W6 added that in using Weight-Mate to look at the progression of the set, it becomes easier to identify when the technique starts failing due to fatigue.

"It's super cool to be able to see and analyse 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 red and green colour choice for respectively incorrect and correct posture was intuitive to follow 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 manage to register it, this especially happened with W10.

Textual Feedback

The textual feedback helped the weightlifters emphasise each mistake in each repetition. It was praised for being short and precise, and helped the weightlifters get a faster overview of the mistakes made in the set. It also helped them to verify that the mistakes they saw in the animation correlated with the textual feedback. W9 did not notice the textual feedback, because the animation was enough to get an understanding of what was correct/incorrect in the set. One concern raised by W10 was that the text did not tell her how wrong she was and how to correct it and she would like more critical mistakes to be highlighted.

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

Five weightlifters commented on the on-screen repetition counter, where all were positive, saying that it was a good way to keep track of their repetitions if they forget to count the repetitions themselves and the repetition counter did not distract their lift.

Combining Feedback Modes

The sequence of audio and visual feedback is meant to aid the weightlifters in perfecting the deadlift. It is therefore vital that the feedback is accessible and useful for the weightlifter.

Both the audio and visual feedback designed into the system was deemed useful by the weightlifters.

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

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 had trouble knowing how to correct their mistakes and also wanted to know to a specific degree how much they should correct their movement. For instance, when W10 would get the feedback message "Move your hips higher", she would like to know how much higher.

Lift Performance

The weightlifters' performance is a crucial part of the evaluation to verify if it has helped the weightlifters perfecting their deadlift.

Five weightlifters reported on a noticeable positive difference from their first or second set to their third set by following the feedback given by Weight-Mate.

Furthermore, the data generated from the IMUs supports indicated that the weightlifters were perfecting their deadlift by making less mistakes. W10 had multiple lifts in the third set, where she did not 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*

We noticed that in the first set, most of the weightlifters stopped briefly to listen to the feedback the first time, but after that initial experience of the feedback, the weightlifters would continue to lift while receiving feedback. After the first set, the weightlifters were accustomed to the audio feedback and said they were not distracted by the feedback instructions, because they knew what to expect and how they would get feedback in the next set.

None of the weightlifters mentioned being hindered in performing the deadlift to the best of their ability. W5 describes it as virtually no difference between deadlifting with the Weight-Mate suit on and deadlifting normally in a fitness centre.

DISCUSSION

Through the study of Weight-Mate in use, and through iterative design refinements based on user feedback, we were able to establish an improved design for the Weight-Mate suit, to design relevant audio and visual feedback to be used in specific parts of the weightlifting activity, and we helped our lifters to achieve an improved deadlift performance. This was supported by iterative refinement of the technical specifications of the system.

Design of the Weight-Mate Suit

The suit was reported comfortable to wear and it offered the weightlifters a cool and engaging experience using Weight-Mate. We did, however, find limitations with the suit. Each sensor requires four wires from the sensor to the FLORA board, which means that the shirt of the suit would have 32 wires running down the back causing the webbing to thicken. This lead to some unforeseen problems when weightlifters would bend their back as the sensors would not follow properly. Furthermore, it also meant that we could not hide the FLORA mainboard in the pocket inside the suit without compromising the data from the bottom sensor on the back.

Audio and Visual Feedback

It was clear that there was a learning curve to Weight-Mate, but getting used to the system happened fairly quickly. Each time a new audio instruction was given, during the lift, the weightlifter had to take a second to process this information. The same was apparent in the retrospective playback, where the weightlifter would look around the screen after the first set to figure what was going on. In the following retrospective playbacks the weightlifter was following the sequential order of the repetitions without looking aimlessly around the screen.

The decision to change the audio feedback from English to native language was received positively amongst all the weightlifters, and based on interviews with weightlifters, who also participated in the formative evaluations, it was clear that a native real voice was better than a computer generated English voice.

The retrospective playback, at the end of each lift, played a vital role for the weightlifters to get an understanding of how well they performed their entire sets and where their posture problems were.

Improved Deadlift Performance

The perceived improvement of the deadlift was achieved through getting accustomed to receiving feedback while deadlifting and the learning curve of the Weight-Mate system. The noticeable difference from the first set to the last set could be a result of the lack of the weightlifters' warm up, even though they were instructed to do warm up properly as they would before a normal training session. Therefore, their first set was used to get into the correct mindset and movement of deadlifting. However, if this was the case for some weightlifters, then Weight-Mate still serves a meaningful purpose because if the weightlifter did not warm up properly the technique of their deadlift becomes even more crucial to avoid injuries.

The fact that none of the weightlifters had their knees exceeding their toes during their deadlifts is interesting. It validated that our weightlifters are experienced lifters, and it showed that knees exceeding toes is not a problem for them and reviewing the evaluation video recording showed that our implementation with math trigonometry of the calf and foot length worked as expected.

Technical Design of Weight-Mate

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 the third iteration of Weight-Mate is that we were not able to capture subtler mistakes of the deadlift in the frontal plane, such as lifting crooked when the weightlifter is extending his body to an upright position or flexing into a downward position. This was included in our initial idea for the Weight-Mate system, but due to hardware and implementation difficulty, and time constraints we chose to disable this feature to focus on core components of the system in the sagittal plane. Further implementation of Weight-Mate would require roll data to be added in the feedback calculation in order to accommodate for these types of mistakes.

The number of sensors enabled in the last iteration of Weight-Mate was much lower than the previous versions. This was due to the FLORA platform not being able to transmit data at a desired frequency to support the Kalman filter, and that we only needed one side of the body to simulate a weightlifter performing the deadlift in the sagittal plane. 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. Due to the high amount of sensors enabled on the FLORA platform, we did not have a surplus of excess electrical power to support a Bluetooth module to make the Weight-Mate system wireless. If we wish to support more sensors and Bluetooth in further iterations of Weight-Mate, we would have to acquire a new platform, which is able to transmit data at a higher frequency and have more electrical power.

Our summative evaluation showcased that it is possible for weightlifters to be assisted with sensory feedback in perfecting their deadlift using a wearable system. Weight-Mate contributes to the HCI research area by identifying the types of feedback that experienced weightlifters are able to receive while under heavy physical pressure during performance of the deadlift. We believe that, not only can this contribution be used for other weightlifting exercises, but also in areas where experienced individuals are under heavy physical pressure, for example workers on a construction site.

CONCLUSION

This research presents Weight-Mate, a wearable computer system that works in conjunction with sensory feedback that assists experienced weightlifters in perfecting the conventional deadlift. In order to accommodate this challenge Weight-Mate was designed and implemented iteratively with intense user involvement.

Wearing the Weight-Mate suit, which is designed to capture the orientation of the weightlifter's body parts, the Weight-Mate system is able to identify misalignments of weightlifters bodies while performing the deadlift and give them appropriate, non-intrusive and timely feedback to help them correct this.

Based on a summative evaluation along with semi-structured interviews we found that, while using Weight-Mate, audio feedback was most appropriate and useful during the lift, and a visual retrospective playback of the lift, after the set of lifts, gave the lifters previously unavailable information vital to improving their technique. This sequence of feedback was reported by the weightlifters as helping them to improve their technique without distracting them from the intense physical and psychological activity of performing the deadlift.

FURTHER WORK

Developing Weigh-Mate was an ongoing process of evaluating the system with weightlifters and refining the system based on user feedback. Due to the time limitation of our Master's project, we chose to have a summative evaluation as the last evaluation in our research. Ideally, if we had more time we would have conducted more formative evaluations and refinement iterations, which could lead to a commercial product.

If we were to continue working with Weight-Mate, we world continue working in iterations with close involvement with the weightlifters, in order for us to continually get some useful user feedback. The formative and summative evaluations were held in a controlled setting, where the weightlifters were watched and recorded during the entire session. We can imagine situations where using Weigh-Mate in a gym would generate or highlight problems that we did not encounter in a controlled environment. An evaluation in-the-wild would therefore be suitable for this system before it is made commercially available. If we were to evaluate it in-the-wild, we would imagine a setting where more people would be inspired to evaluate the system in the gym. This could lead to a more diverse test participation, which may generate different results compared to what we observed in the controlled setting.

As for now Weight-Mate provides feedback on the deadlift exercise. However, the potential of the Weight-Mate suit paves the way for additional weightlifting exercises such as squat, unilateral biceps curl etc. Weight-Mate can also be used when refreshing your technique and when verifying whether the technique is correct when adding more weights to the barbell. For example, the system could incorporate a tempo counter instructing the weightlifter with the right tempo to perform the deadlift, because the tempo of the deadlift is also a measure to keep in mind. In addition, the degree of incorrectness of the technique needs to be visualised so the weightlifter can act on it.

The weightlifters requested more positive feedback from the system. One way to achieve this could be to incorporate personal achievement awards and tokens (as found in popular fitness apps) to promote gamification of the system and increase extrinsic motivation. Another interesting kind of feedback that could be made possible with the Weight-Mate system would be to log statistics of each deadlift and provide visualisations of this over time for the weightlifters to look at between training sessions, and perhaps even use as a training planning tool. It would be good to explore these options in future iterations of the system.

The webbing and wires require a redesign that allows for easy mounting and dismounting, which allows the suit to be machine-washed.

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