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Knee Up: an Exercise Game for Standing Knee Raises by Motion Capture with RGB-D Sensor

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Abstract

In this work, we present the design and the implementation of Knee Up, an exergame that promotes knee health via standing knee raises exercises. It allows users to exercise at home and perform the exercise in a gaming environment. By motion capture using RGB-D data, estimated positions of the user's skeletal joints are acquired and processed in real-time. For the game, 3D virtual environments have been created with gamification elements so that users can enjoy more interactive and engaging exercise sessions. The game facilitates to evaluate the quality of performed standing knee raises exercise through a rule-based recognition algorithm and, in return, to provide timely feedback. A formal user study was conducted in order to assess the usability and gamification aspects of Knee Up. Study results demonstrate that Knee Up is generally well-received in terms of usability, engagement, ease of learning-to-play, and exercise sustainability; and validate that the rule-based recognition algorithm works satisfactorily well.

Keywords: Exergame, Knee Exercise, Motion Analysis, RGB-D, Kinect

1. Introduction

Physical exercises have an important role in helping individuals maintain physical health, feel better and perform their daily life movements properly. Considering that doing exercises under supervision in special therapy centers to be expensive, most individuals rather performing physical exercises at home usually through home exercise sessions. However, repetition and monotony may decrease motivation and prevent the individual from exercising correctly and effectively.

In traditional home exercise programs, exercise movements are presented to the individual either through images or video [ZFL*14, ZREL17]. In such approaches, it is difficult to ascertain the effectiveness of the program as the individual's movements are not under observation. In addition, the individual does not receive feedback regarding the exercise session. McCallum [McC12] indicated that wrong exercise movements could lead to injury or cause the wrong muscle actions in the body.

Presenting the exercise program through a game interface that tracks human motion can help to ensure that the exercise movements are done correctly and in an engaging way. Exergame, short for exercise game, is type of a serious game which incorporates a clinical and/or home-based exercise program with the intent of encouraging people to exercise more regularly by making exercise activity more fun [WBGS13]. The studies show that gamification elements integrated into the exergames motivate people towards regular physical exercise [DKPC11].

The main challenge for an exergame is developing a motion definition language for the classified human body movements in question [HO14]. Another challenge is offering these games to be playable with devices that are accessible for home users. Today, the prevalence of home gaming consoles at affordable prices make these devices a good alternative as exergame media.

From the beginning of 2000s, exergames have become more popular. Exergaming met mass attention in 2003 in the form of an interactive gaming bicycle called Gaming Bike that was targeted for the commercial sports market. In the following years, it was marketed as a sport and exercise equipment that works with video game technology. Introduced in 2005 as such equipment, EyeToy:Kinetic was a novelty for multi-functional home exercise. The game's controller lets the player interact with the exergame environment by superimposing their digitalized live image onto the display screen. In 2006, another novelty exergaming product called Gamercize was introduced. It combined traditional fitness equipment with game consoles [url18c].

In early 2010s, with the emergence of Microsoft's Kinect device (2010) that worked with Microsoft's game consoles as well as PCs, human body movements have been integrated interactively into games. Along with Kinect, Microsoft released Kinect Sports game consisting of six sports simulations, which were ten-pin bowling, boxing, track and field, table tennis, beach volleyball, and association football. In the game, players stand in front of the Kinect sen-

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sor and compete by simulating real-life sports movements. Also, the game has recently started to offer multi-player option [LZ15].

In 2011, Microsoft released a Software Development Kit (SDK) for Kinect. The SDK allowed developers to start integrating Kinect functionality to computer-based programs. Saenz-de-Urturi et al. [SdUGZMZ15], and Saenz-de-Urturi and García-Zapirain Sato [SdUGZS16] proposed systems that make use of the SDK to determine wrong movements in real-time while the elderly perform physical activities via a virtual 3D exergame that was developed for promoting posture health. Furthermore, Antón et al. [AGI15] proposed a system which facilitates therapeutic exercise programs. With the system, the transformed coordinates of the 3D points captured by the Kinect sensor are calculated for 3 types of measurements, which are positions of body joints, the angles between the joints, and the angles between the limbs. After the posture is captured, the corresponding identifiers are generated and used for posture classification. Zhao et al. provide a concise tutorial and methodology on the state-of-the-art research of human motion tracking and recognition with Kinect [ZFL*14, Zha16, ZREL17].

In [CP16], a tracking software was designed to control the squat exercise's correction using Kinect V2 sensor. The controlling process was done by angles and rules based on these angles. Garcia et. al. [GPTN14] developed Step Kinnection as an interactive step training system for elderly people to overcome the fear of falling. The application uses the Kinect sensor to track the player's feet. In the software, there are six virtual panels on the screen and the player is expected to step on the green one as fast as possible. In another system [GA12], which was designed to motivate elderly people to participate in exergames, regular performance of arm raising exercises are promoted in a fun and motivating way.

Garrido et. al. [GMPL13] developed a system to control the balance in walking exercise. The system is based on a specific framework that analyzes the movement of patients using the Kinect sensor in order to generate adequate corrections during the rehabilitation process. REOVIEM [LQGGGG*13] is another example of a Kinect-based exercise system. It offers three motor rehabilitation exercises, namely TouchBall, TakeBall and StepBall, for multiple sclerosis rehabilitation. The system also allows therapists to control the rehabilitation sessions and monitor the patient's development processes.

Exergaming has seen a recent surge in popularity due to the success of the Nintendo Wii console. Nintendo Wii and Microsoft Xbox with Kinect have revolutionized exergaming by focusing on the fundamentals of gameplay and thus appealing to a much wider population than previous devices [PSM*16]. Consequently, several physical therapy centers, university laboratories as well as many home users have adopted the use of exergaming applications. With the progress of hardware technology and the increase in the research efforts, the use of exergames in physical rehabilitation and exercise programs bears the potential to be even more successful and motivational [SMB*10, DRMB09].

2. Knee Up: System Design and Implementation

In this work, a Kinect based exergame called Knee Up is designed and implemented for Standing Knee Raises Movement (SKRM) exercise. A rule-based algorithm was developed for recognition of player's stand still pose (SSP) and SKRMs in order to provide real-time feedback to the player and to log the progress of the player in detail for further evaluation. For the algorithm, separate sets of validation rules for the static pose and dynamic movements have been created. Various gamification elements have been employed within the game to make it more entertaining for sustained exercise activity.

While developing the system, we had the following objectives:

- To recognize player's SSP correctly in real-time,
- To recognize SKRM performance correctly in real-time,
- To facilitate learning how to do SKRM correctly,
- To provide sustainability of exercise by using gamification,
- To provide real-time feedback to the player,
- To keep player's session history including score and exercise data for further analysis.

2.1. Online Human Motion Capture from RGB-D Data

In order to satisfy the above objectives, firstly RGB-D data stream from Kinect sensor has been integrated to work with the game. For

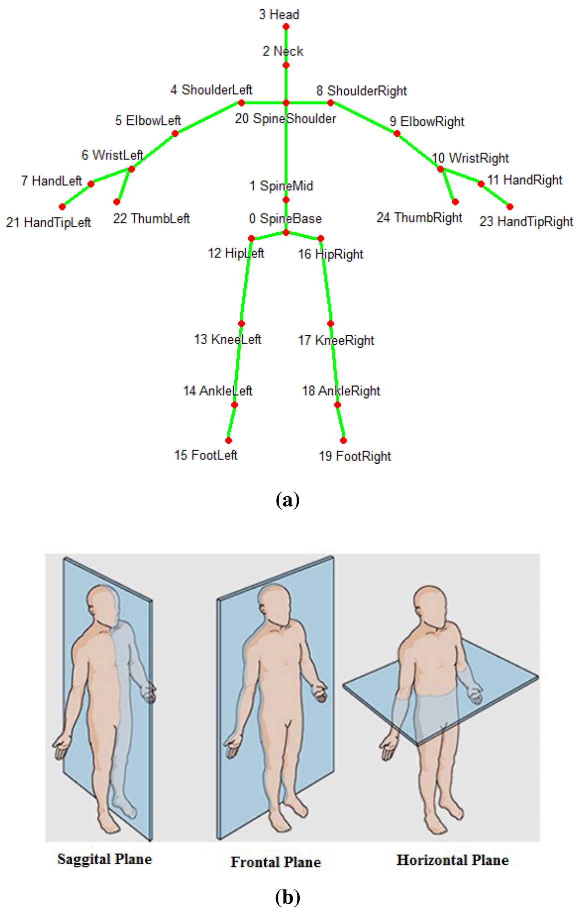


Figure 1: *(a) Joint hierarchy [url18b]. (b) Human body planes [url18d].*

this work, we made use of Kinect for Xbox One (Kinect V2), which is the hardware upgraded version of the original. The system processes the captured RGB-D data and recognizes the player's pose in real-time by estimating positions of 25 skeletal joints (Fig. 1a) in three dimensional coordinates. With the joint position data, the vectors connecting those joints are determined and used for obtaining distances between the joints, as well as the angles between the vectors.

2.2. System

The system, comprising online human motion capture module, implementation of our rule-based SSP and SKRM recognition algorithm (detailed in 2.4), two-dimensional menu screens and three-dimensional virtual environments, was realized using Unity graphics engine. Three-dimensional virtual environments consist of the test phase and the game. These environments, including the scenery, the avatar character and the obstacle characters, have been created by using low-poly (i.e., made up of a relatively small number of polygons) three-dimensional models. Low-poly models help to provide a streamlined gaming experience even when Knee Up is run on low-end contemporary PCs with limited graphics processing capability. Another reason to opt for low-poly models was that they present the added benefit of exhibiting minimalist and retro-style aesthetics which contemporary audiences tend to find pleasing.

When the application starts, the player is greeted with the login screen (Fig. 2). Here, the player creates a new user profile if it is their first time with Knee Up. Player profiles let the system to keep each player's session history, including overall progress and session scores, uniquely associated with them in the database. If they are a returning player, they are asked to provide their login information so that they can proceed with their existing profile.

A first-time player of Knee Up initially enters the test phase before starting to play the game. The test phase serves two purposes. The first is to teach the player how to perform SKRM correctly. The second is to acquire a baseline for that player profile by recording player's initial SSP and the measurements at peak raised-knee poses to asses the player's SKRM motion range. With SSP, the static skeletal measurements required for the recognition algorithm are taken. The player needs to perform 10 SKRMs (5 per knee) correctly to be able to continue to the game.

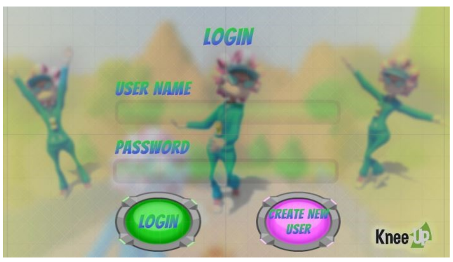


Figure 2: *Login screen of Knee Up game.*

2.3. Gamification

In the game, gamification elements have been heavily used with the aim of making SKRM exercise more fun and motivational for players. The main objective of the game is not to hit the obstacles by doing SKRM properly. The game provides real-time feedback for the performed SKRM (Fig. 3). In order to increase appeal, the obstacles are in 10 different variety and characterized as animals in boxy shapes. They appear randomly on either flank of the avatar character that the player controls with full body movements in front of Kinect.

Once an obstacle appears over the horizon, it begins moving towards the avatar in two different modes, one of which the player chooses at the beginning of the game. In the first mode, they move at fixed time intervals at a constant speed. The time interval can be set to 60, 90 or 120 seconds by the player. In the latter mode, they move at fixed intervals with incremental speed. The maximum speed is four times the start speed v. When the player performs SKRM accurately five consecutive times, the speed of the obstacles increases by $0.1v$. If the player hits an obstacle or fails to do a proper SKRM five consecutive times, the speed decreases by $0.1v$.

On the other hand, scoring is solely based on SKRM performance regardless of the interaction with the obstacles. For each knee-raise performed properly, 10 points are added to the score. Further, when the SKRM cycle is completed with proper knee-down, another 5 points are added. During the game, the real-time score information is displayed on top of the gaming interface and logged in the player's profile.

Figure 3: *Instances of right (✔) and wrong (✖) SKRM performances during the game.*

2.4. Rule-Based Recognition Algorithm

The recognition algorithm constitutes the essential backbone of Knee Up. For its design, we had the following main goals:

- The algorithm needs to be light, i.e., needing as little computational resource as possible, so that it can run on a wide range of systems including low-end contemporary PCs with limited resources.
- The algorithm needs to be fast so that the system can provide real-time feedback to the player. As the system comprises other modules that also need to run in real-time, the algorithm must be in tandem with them.
- The algorithm needs to exhibit high precision in its classification so that the feedback received by the player is not only timely but also accurate.

As Projected onto the Sagittal Plane (concerning vertical coordinate components only)	As Projected onto the Frontal Plane (concerning horizontal coordinate components only)
Head joint position must be greater than Neck joint's	HandLeft joint position must be smaller than HipLeft joint's
Neck joint position must be greater than SpineShoulder joint's	HandRight joint position must be greater than HipRight joint's
SpineShoulder joint position must be greater than SpineMid joint's	KneeRight joint position must be greater than KneeLeft joint's
SpineMid joint position must be greater than SpineBase joint's	AnkleRight joint position must be greater than AnkleLeft joint's
HipLeft joint position must be greater than KneeLeft joint's	ShoulderRight joint position must be greater than KneeRight joint's
HipRight joint position must be greater than KneeRight joint's	ShoulderRight joint position must be equal or greater than AnkleRight joint's
KneeLeft joint position must be greater than AnkleLeft joint's	ShoulderLeft joint position must be smaller than KneeLeft joint's
KneeRight joint position must be greater than AnkleRight joint's	ShoulderLeft joint position must be equal or smaller than AnkleLeft joint's
ShoulderLeft joint position must be greater than ElbowLeft joint's	
ShoulderRight joint position must be greater than ElbowRight joint's	
ElbowLeft joint position must be greater than WristLeft joint's	
ElbowRight joint position must be greater than WristRight joint's	

Table 1: *SSP rules.*

To achieve the goals above, we adopted a rule-based approach in our algorithm. It is used for recognizing both correct SSP and correct SKRM. The algorithm observes a set of rules for SSP and SKRM that are defined separately and implemented into the game. The rules are encoded in XML format with a motion definition language that we developed particularly for this work.

Rules for the SSP checks seventeen joint positions as projected onto the sagittal plane and ten joint positions as projected onto the frontal plane (Fig. 1). For a proper SSP, head should be straight; shoulders should be at the same level, not curved forward or backward; and feet should be about shoulder width apart. Also arms should be down the sides of the body [Win95]. The complete set of SSP rules, based on the specified joint positions for sagittal and frontal planes, are given in Table 1.

When starting SKRM, the player should stand tall with legs straight and arms hanging by side. Then they begin by lifting one knee up reaching the waist level and keeping there as close as possible to a 90° angle at the knee. After the movement is completed by lowering the knee down, player will repeat for the other knee. During the movement, the player should be stretching through the glute and hamstring muscles. Also it is important to keep the abdominals tight to help with the balance [url18a].

In order to recognize SKRM based on the definition above, four rules are created based on the definition of movement. The first is that the knee should be lifted up to the chest without disturbing the body stand. The second rule is for keeping the abdominal muscles tight while performing the SKRM. These two rules are created to protect the balance by keeping the muscles tight. The third rule is that the player lifts the knee straight forward, not to the right or the left side of the body while lifting the knee up. And the last one is simply to verify the completion of SKRM: the lifted leg must be lowered back to the ground.

The rules, as described above, cover five joints for left- and right-knee-up movements in sagittal plane, frontal plane and transverse plane separately (Fig. 1b): two spine joints (SpineShoulder and SpineBase), one hip joint (HipLeft or HipRight), one knee joint (KneeLeft or KneeRight), and one ankle joint (AnkleLeft or AnkleRight). The positions of these joints are used to determine the vectors that connect them.

Angular ranges need to be defined when incorporating the rules in the algorithm. In order to determine these ranges, a set of preliminary trials were carried out with six volunteers who were asked to perform SKRM. The data observed during these trials have been used to designate the ranges of proper motion during the exercise. The angular limits should be specified in a way that lets the game to be playable by all adult age- and body-type-groups. Therefore, a ± 5° tolerance was applied to the observed angular extrema as in $range_{min} = 5 * round\left((trials_{min} - 5)/5\right)$ and $range_{max} = 5 * round\left((trials_{max} + 5)/5\right)$.

For two vectors $\overline{AB}$ and $\overline{BC}$ that are specified by the positions of the joints A, B and C, the algorithm finds the angle α between the two vectors via the dot product as in

$$\alpha = cos^{-1}\left(\frac{\overline{AB}\cdot\overline{BC}}{\left\|\overline{AB}\right\|\left\|\overline{BC}\right\|}\right)$$

where $\left\|\overline{AB}\right\|$ is the Euclidean distance between the joints A and B.

The algorithmic analogues of the SKRM rules are given below. For the sake of brevity, they are given for SKRM with right-knee-up only. For rules pertaining to SKRM with left-knee-up, joints that are specific to the right-side are replaced with their left-side counterparts (e.g., KneeRight to KneeLeft). The algorithm automatically detects which leg is raised for SKRM and starts the rule-based recognition cycle accordingly.

Algorithm Rule #1: θ is defined as the angle between SpineBase-SpineShoulder and SpineBase-KneeRight vectors (Fig. 4a). According to the trial results, range of θ was between 48.1° and 104.9°. With the added tolerance, the first rule is satisfied for 45° $< \theta <$ 110°.

Algorithm Rule #2: ϕ is defined as the angle between KneeRight-HipRight and KneeRight-AnkleRight vectors (Fig. 4b). According

(a) **(b)** **(c)**

Figure 4: *(a) θ angle. (b) ϕ angle. (c) ψ angle.*

to the trial results, range of ϕ was between 43.1° and 93.8°. With the added tolerance, the second rule is satisfied for $40^\circ < \phi < 100^\circ$.

Algorithm Rule #3: ψ is defined as the angle between HipRight-SpineBase and HipRight-KneeRight vectors (Fig. 4c). According to the trial results, range of ψ was between 89.5° and 128.6°. With the added tolerance, the third rule is satisfied for $85^\circ < \psi < 135^\circ$.

Algorithm Rule #4: Once the first three rules are satisfied, the algorithm needs a check for the fourth rule to validate that SKRM cycle is completed, i.e., the raised leg is lowered back. Hence, the algorithm checks the angles θ and ϕ that were defined for the first two rules for the angular ranges that indicate the completion of the cycle. Results of the trials with the six participants dictate that each of these angles need to be either below 5° or above 140° for the fourth rule to be satisfied.

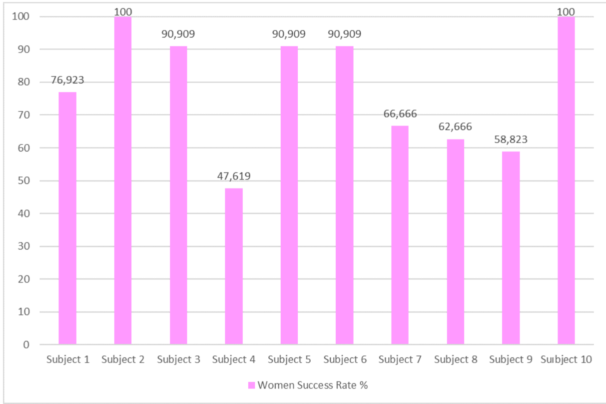
3. User Study

We conducted a formal user study to evaluate performance and usability of Knee Up system. The study was also aimed to test whether the exergame has a positive effect on people. Ten female- and ten male-volunteers participated in this study. The only exclusion criteria were a history of prior knee injury or a pre-existing knee problem. The participants were asked to play the exergame and then to evaluate 11 different questions/statements on a Likert scale of 1 to 5. The evaluated questions/statements along with the collected responses are outlined in Figure 6, and discussed below.

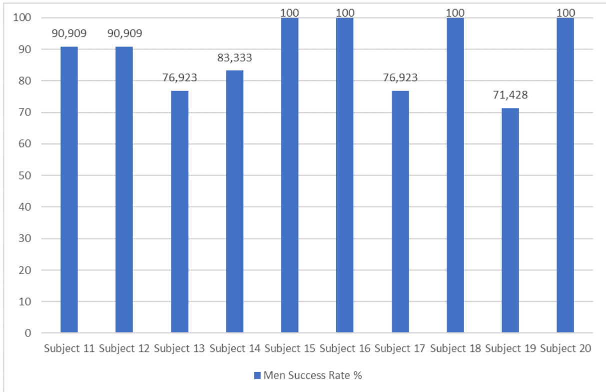
The age distributions of participants are given in Figure 6a. The values of minimum, maximum, average and standard deviation, and standard errors of the female participants' ages are 27, 54, 34.2 and 7.67, and 2.42, respectively. The corresponding values for the male are 32, 57, 41 and 9, and 2.85, respectively. The average age of all 20 participants is 37.6.

Before playing the exergame, each participant's initial range of knee motion is assessed during the test phase. As mentioned before, in order to pass the test phase, a participant is required to do SKRM correctly five times with each knee, totaling 10 proper SKRMs. The rate of correctly performed SKRMs, up to and including the 10^{th} correct movement are given in Figures 5a and 5b, respectively. The average success rate of the participants is 83.79%.

When a participant performs SKRM correctly, θ, ϕ and ψ angles at the peak raised-knee position indicate a participant's range



(a)



(b)

Figure 5: *Success rates for (a) female participants (b) male participants.*

of comfortable knee motion. These angles, as recorded in the test phase for each participant, are given in Figure 7. In the figure, a vertical line is bounded by the minimum and the maximum of the angles attained by that participant at the different peak raised-knee positions of the five correctly performed SKRMs with the designated knee. Average of the same five angle computations is also marked on the same line.

According to the responses to the questionnaire, 15% of the participants never did physical exercises (Fig. 6b). Fig. 6c shows that 35% of the participants (7 people) never play computer games. Only one person plays computer games very often. 70% of the participants do not use extra equipment, such as Kinect, while playing games (Fig. 6d). On the other hand, no one often use an extra equipment other than the controller. This finding hints that the tendency towards adopting new interfaces such as Kinect in game playing is not high within the sample. Almost 55% of all volunteers (11 people) found the physical therapy fees to be expensive or very expensive (Fig. 6e). It is noteworthy that there is no participant who finds physical therapy fees cheap.

It appears that 70% of the participants found Knee Up enjoyable to some degree (Fig. 6f). According to the responses, almost 80%

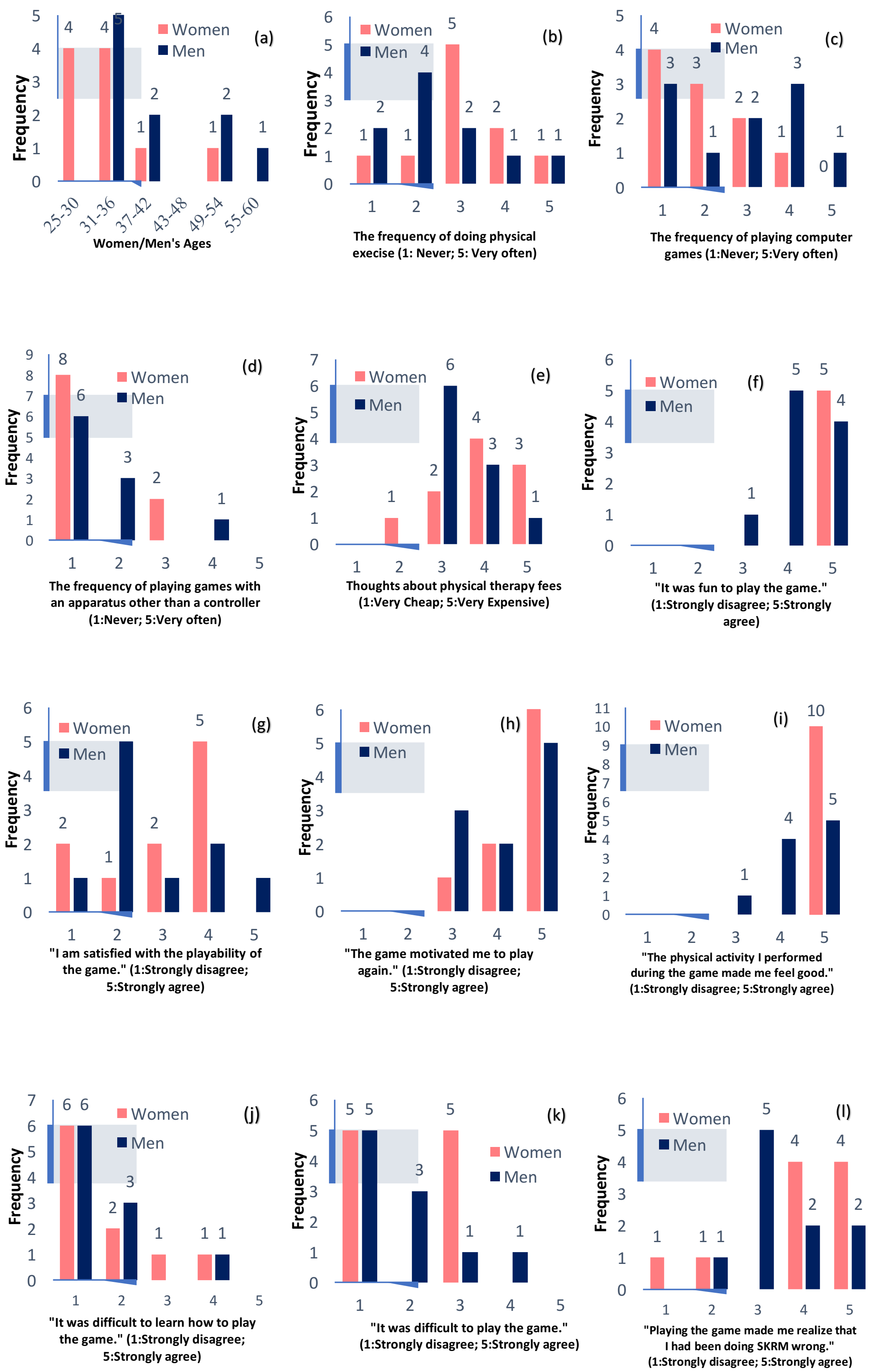


Figure 6: *Frequency distributions of the volunteers' ages (a), and responses (b-l) to the questions 1-11.*

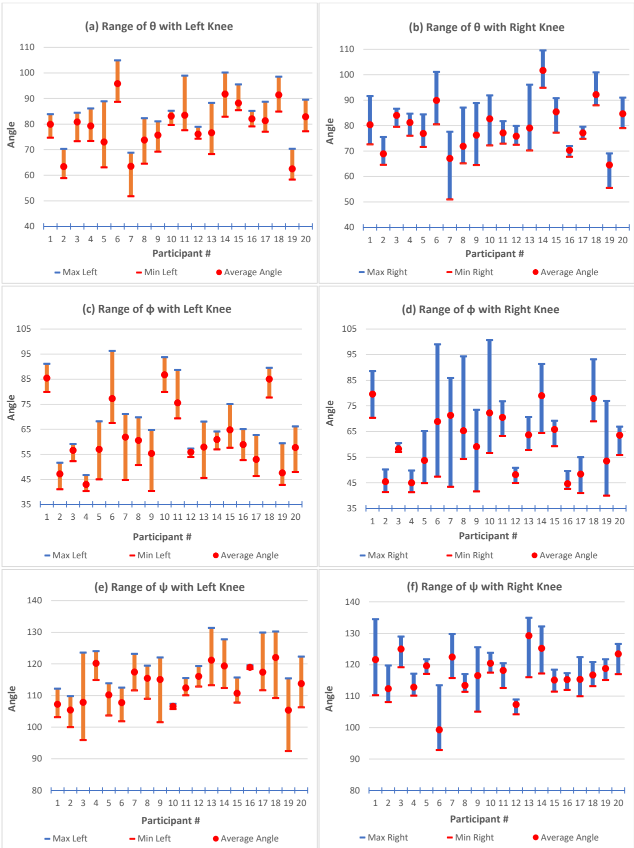


Figure 7: *The range of angles attained by each participant at the peak raised-knee positions of the five correctly performed SKRMs with the designated knee are shown.*

of the participants found the exergame to be motivating to play it again (Fig. 6h). Figure 6i indicates that 75% of the all participants felt well due to the physical activity that they performed during the game.

Figure 6g shows that 40% of the participants were satisfied with Knee Up's playability. This finding urges us to explore this aspect further as it contrasts with findings regarding other associated aspects of the game, especially with Figure 6f. It also hints that we could have benefited from framing this question's statement more in layman's terms since the exact meaning of the term *playability* is hard to grasp intuitively for those who are not familiar with the field.

When all participants are taken into account, 85% of them (17 people) found learning to play Knee Up not difficult (Fig. 6j). In addition, 65% of the participants stated that the game control was not difficult either (Fig. 6k). Figure 6l indicates that 60% of the participants (12 people in total) realized that they had not been doing this exercise right. These findings are also remarkable as they signify that Knee Up may facilitate not only to motivate people to do the exercise in an entertaining video game setup that is easy to learn, but also to effectively help people learn to do the exercise correctly.

Finally, as we present the data in Figures 5 and 6 separately for female and male participants, we look into how significant the difference between the age distributions of the two groups. Variance analysis of the female- and male participants' ages with $\alpha = 0.05$ using t-test and F-test [KM72, WMMY93] shows that $t_{calculated} = 1.82$ and $F_{calculated} = 3.30$. T-test is used to test whether the averages belonging to two groups are different from each other and F-test, analysis of variance is used to determine whether there is a difference between groups based on a particular variable. The comparisons of the calculated values with the standard table values indicate that there is no significant difference between ages of the female and male participants' ages and between two groups. This hints that the number of volunteers can be evaluated as 20 people regardless of gender.

4. Conclusion

We presented Knee Up, an exercise game that is aimed to motivate the regular performance of Standing Knee Raises Movement (SKRM) exercises within a video game setting. To the best of our knowledge, Knee Up is the first exercise game purposed for this specific exercise.

It was important to make Knee Up accessible for majority of adult home-users. While the system has various parts that need to work together in real-time, such as the rule-based recognition module, the motion capture module and the 3D graphics framework, the overall implementation is streamlined so that it runs seamlessly on most contemporary systems. Therefore, Knee Up is ready to be released for home-users, since, other than a computer, the only equipment necessary to play the game is the Kinect sensor which is affordably priced.

The rule-based recognition algorithm fulfills the intended design criteria as it runs in real-time while performing recognition with high accuracy and not requiring extensive computing resources. For the algorithm, we developed two sets of rules, one for the static stand still pose (SSP) and one for dynamic SKRMs. We also developed a motion definition language for encoding those rules in XML format. Therefore, the rules for recognition of different exercise movements can be easily added to the system in future.

Through a formal user study with 20 participants, we validated the usability of Knee Up by adult players in various age groups (Fig. 6a). The study sample represents a wide range of adult users from avid computer game players to those who rarely play (Fig. 6c). The study demonstrates that Knee Up is generally found to be fun, easy-to-learn, easy-to-play and motivating for sustaining the exercise (Figures 6- f, j, k and h, respectively). The results of the study also validate that the rule-based recognition algorithm has high precision, as none of the participants found the game frustrating (Fig. 6f) and all but one of them stated that they did not find it difficult to play (Fig. 6k). The efficacy of Knee Up within a physical rehabilitation program for those with knee injury history should be validated by a separate study with a larger sample encompassing those with prior and/or ongoing knee problems.

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