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# Fun-Knee™: A Novel Smart Knee Sleeve for Total-Knee-Replacement Rehabilitation with Gamification

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**Abstract**—Total Knee Replacement (TKR) is an increasingly common surgery worldwide. A significant contributor to TKR success is post-surgical rehabilitation. In this work, we present Fun-Knee™, a novel sensor-equipped knee support complemented by mobile device-supported games, specifically designed for “gamified” TKR rehabilitation. Two inclinometers are used to measure the knee angle, which is used as the main input to the developed game. Human-Centered Design theory is applied throughout the game design to ensure a customized, dynamic gaming experience to maximize the pain distraction effect and to increase the exercise compliance and improve the rehabilitation outcome. Preliminary survey results collected from practicing physiotherapists show promising outcomes of the developed prototype, in terms of hardware and software characteristics, usability, clinical utility and overall effectiveness.

## I. INTRODUCTION

Knee osteoarthritis is one of the most common degenerative conditions in older adults [1]. For these patients, *Total Knee Replacement* (TKR) is the gold standard treatment for pain and deformity persists despite conservative treatment. The number of TKRs is on an increasing trend, worldwide.

A significant contributor to TKR success is post-surgical rehabilitation [2]. Poor rehabilitation can lead to decreased knee range of movement and strength. This may predispose patients to secondary musculoskeletal complications, poorer functional outcomes, lower satisfaction and prolonged rehabilitation duration.

In this paper, we present Fun-Knee™, a sensor-equipped knee support complemented by mobile device-supported games. The knee support component is a free-sized knee sleeve, fitted with inclinometers and Bluetooth modules. The games target at training specific movements with evidence-based rehabilitation exercises. Jointly, they allow monitoring of knee position; providing real-time feedback as patients are guided through “gamified” rehabilitation exercises. Fun-Knee™ aims to improve exercise compliance, effectiveness and care continuity, while creating a more engaging and positive rehabilitation experience for patients.

The rest of this paper is organized as follows. Section II introduces some background on TKR. Section III presents related work. Section IV presents our hardware system. Sec-

tion V presents our game design. Section VI presents some preliminary results on user studies. Section VII concludes with discussion on future work.

## II. TKR REHABILITATION BACKGROUND

Knee Osteoarthritis (OA) is reported in over 34% of older adults aged 63 to 94 years old. As populations gray, the incidence of OA will rise [2]. We will see a corresponding increase in the volume of TKRs performed. Advancements in surgical techniques and implant technology have benefitted patients, but an effective post-operative rehabilitation remains crucial for optimal functional recovery. Conventional rehabilitation begins after TKR. At least 70% of TKR patients in our institution require outpatient physiotherapy follow-up [3].

The optimal window for TKR rehabilitation is in first three to six months post-operatively. Inadequate rehabilitation leads to poor knee range of movement, muscular weakness, movement limitation, functional disability and patient dissatisfaction. Physiotherapy-based rehabilitation begins immediately post-TKR to facilitate timely recovery of muscular activation, range of movement and function. Recent literature even recommend pre-operative rehabilitation to maximise post-operative gains. Conventional TKR rehabilitation follows a largely therapist-directed, manpower-intensive model of care. After surgery, patients await a twenty to thirty minute session of physiotherapy, once a day. Upon discharge, patients receive a booklet of common post-TKR exercises, with no form of contact with the physiotherapist until two to three weeks later.

Over the past two years, data of TKR patients have been tracked through their recovery in Tan Tock Seng Hospital (TTSH), Singapore. It was found that majority of patients’ knee movement had poor maintenance, and even worsening, in the initial two to three weeks after hospital discharge. Between hospital discharge and outpatient physiotherapy follow-up, 25% of patients worsened in knee bending movement and 65.3% worsened in knee straightening movement. Of the patients who had worsened knee straightening performance, majority lost more than 10 degrees of movement, which is of clinical significance [3]. Poor recovery of knee range of movement can predispose patients to musculoskeletal

complaints, reduced mobility, increased implant stress and prolonged rehabilitation.

An investigation was done to identify potential reasons for poor knee range post-discharge. Three main problems were identified in the post-discharge phase of rehabilitation:

- 1) Poor exercise compliance: patients find the repetitive exercises boring and unengaging
- 2) Poor exercise effectiveness: the hardcopy exercise printouts do not ensure quality in knee movements. Patients often forget how to perform their exercises accurately and forfeit therapeutic benefits despite diligence.
- 3) Poor care continuity before outpatient physiotherapy: Despite exercise-based rehabilitation being the key feature after TKR, there is no available feedback or monitoring in the initial 2 to 3 weeks after hospital discharge.

There are currently no existing solutions targeting the above barriers that contribute to poor physical outcomes, prolonged rehabilitation and reduced cost-effectiveness in TKR rehabilitation.

### III. RELATED WORK

Recently, motion tracking and gamification have been combined in many rehabilitation studies. In these studies, Microsoft Kinect and Nintendo Wii are the two most popular commercialized motion tracking devices used. Martins et al. [4] have developed a system for patients with severe motor disabilities due to neurological diseases using Kinect. Menezes et al. [5] have developed a similar system aimed to provide aid in physical and motor rehabilitation. Lam et al. [6] have developed a Kinect-based automated rehabilitation system specifically for the clinical environment. Portela et al. [7] have demonstrated positive effects of serious games using Wii on physical and mental domains. All of the above studies have proved their capability in movement tracking and concluded that such systems could help to improve patients' conditions.

However, these approaches have their limitations. Torrao et al. [8] mentioned constrains in detecting Z axis (the axis perpendicular to the sensor) movements and pointed out that high speed movement may results in inaccurate reading when using Kinect. Su [9] has pointed out that Kinect has limited fine movement detection. The Wii system is not designed to detect movement of body parts other than the hands. Since basic TKR rehabilitation exercises requires the patient to remain in a specific position to ensure accurate knee angle detection (one degree accuracy), Kinect and Wii platforms are not ideal for TKR patients.

Customized wearable sensors are also widely used for motion tracking. Jun [10] has developed a knee brace and has demonstrated how sensors combined with mechanical structure can provide support in knee rehabilitation. Morais and Wickstorm [11] have designed a wristband with Shimmer wireless sensor platform embedded for tracking Tai Chi gestures. Moreira et al. [12] have developed a motion tracking glove for rehabilitation and animation. These studies have demonstrated that wearable sensors can offer accurate measurements, have good reliability and low cost. Ayoade and

Baillie [13] and Torres et al. [14] have developed systems using wearable sensors for TKR rehabilitation. However, the former system did not have much gamification elements and they reported a vast decrease in patients' engagement as their study progressed. The hardware of the latter system has a dimension of  $2.7 \times 3 \times 1.5$  inches and weighs 142 g, which we believe can be greatly improved.

Besides hardware, the design of rehabilitation games also plays a significant role. Although the aforementioned studies include some games in their systems, few exploit the potential of game design. In fact, very few studies have explored rehab-specific game design in detail. Awad et al. [15] proposed some game design principles that can be used to design games for older adults. Their paper concludes that it is important to consider the player's capabilities when designing a movement based game for older adults and the presentation of the visuals should guide the player's actions. Lohse et al. [16] pointed out that eight key factors need to be considered when designing games for older adults in order for the game to be motivating and effective. Their work demonstrates the huge potential game design has on improving patients' rehabilitation process. Alankus et al. [17] have developed a series of games for stroke rehabilitation that emphasized on playability, therapeutic value, fun and challenging.

Alankus et al. [17] highlighted that cognitive capability is an important consideration in game design in general. Pain is a problem that all TKR patients face during their rehabilitation and according to Eccleston and Crombez [18], pain demands attention and affects cognitive capability. They have also identified several characteristics of pain stimuli which may vary the amount of attention demanded. Some rehabilitation studies have considered patients' pain problems, however, most of them try to avoid causing pain instead of tackling it [19], [20]. A common way to tackle pain is through distraction. Using functional MRI to image brain activity, Bantick et al. [21] have proven that tasks that demand attention can modulate the perception of pain. They found that significantly lower pain intensity scores were reported when test subjects were engaged in a more cognitively demanding task than in a neutral condition. Liu et al. [22] summarized several virtual reality systems that were developed to manage pain and distress associated with painful medical procedures. However, based on our knowledge, implementation of pain distraction features in non virtual reality systems for rehabilitation is lacking. Pain distraction is an important element in Fun-Knee™, where the patient's cognitive capability has been carefully considered in our game design.

### IV. SENSOR EQUIPPED KNEE SLEEVE

We introduce Fun-Knee™ in this and the next section, describing its hardware and software design in detail.

The most crucial quantitative measure for TKR rehabilitation movement is the knee angle. Thus, we center our design of Fun-Knee™ around this attribute. A portable and low cost sensor system has been developed to be mounted on a knee sleeve for knee angle measurement. The system consists of

two altitude measurement modules (JY901) and one Bluetooth transmitter (CC2541) as shown in Fig. 1. The JY901 module uses an MPU-6050 motion tracking device as its sensing and processing unit. The MPU-6050 is embedded with a 3-axis Microelectromechanical (MEMS) gyroscope, a 3-axis MEMS accelerometer and a Digital Motion Processor (DMP). The Kalman filter is used to filter its output. The final data accuracy is up to 0.05 degrees. A rechargeable lithium battery is used as the power source of the system. A four-hour running time with a two-hour charging time has been realized.

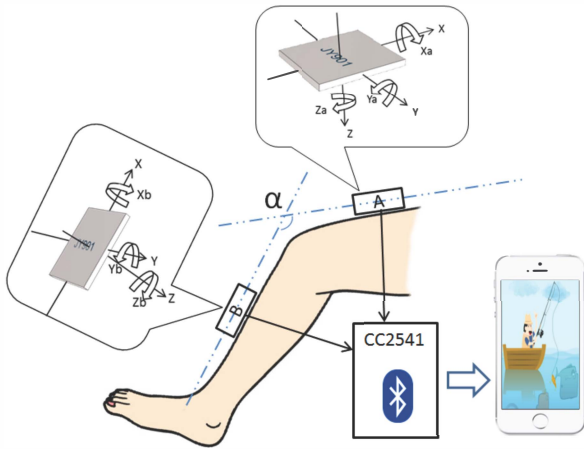


Fig. 1. Sensor System

The two JY901 modules are placed above and below the knee joint, respectively. They are both connected to CC2541 through a shared i2C data bus. The CC2541 Bluetooth transmitter combines readings from both JY901 modules and send them at a 5Hz rate to the game device for angle calculation. The system schematic is shown in Fig. 2.

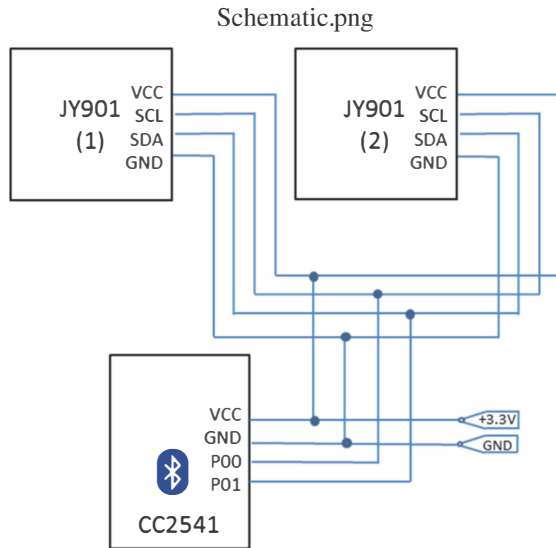


Fig. 2. Schematic of Sensor System

**Knee angle calculation:** Readings of JY901 are Tait-Bryan

angles in East, North Up (ENU) convention with rotation sequence of z-y-x (intrinsic) [23]. In our set-up, the Pitch (Y-axis) angle of the two sensors, which can be directly used to calculate knee angle, always falls in the  $\pm 90$  degree range. To ensure the calculation is correct regardless of a patient's stance, the Roll (X-axis) angle is used to discriminate different stances. The Yaw (z-axis) angle is not needed for this calculation. Regards to the positioning shown in Fig. 1, knee angle  $\alpha$  is calculated using the following formula:

$$\alpha = \begin{cases} 180 - Y_a + Y_b, & \text{if } |X_a| > 90 \text{ and } |X_b| > 90 \\ 360 - Y_a - Y_b, & \text{if } |X_a| > 90 \text{ and } |X_b| \leq 90 \\ Y_a + Y_b, & \text{if } |X_a| \leq 90 \text{ and } |X_b| > 90 \\ 180 + Y_a - Y_b, & \text{if } |X_a| \leq 90 \text{ and } |X_b| \leq 90 \end{cases} \quad (1)$$

$Y_a$ ,  $Y_b$  and  $X_a$ ,  $X_b$  are Pitch and Roll angles from each sensor (a and b) respectively.

## V. FUN-KNEE™ GAME DESIGN

The design of the Fun-Knee™ rehabilitation game follows the Human-Centered Design theory [24]. TKR patients' needs, capabilities and current rehabilitation methods have been carefully examined during a two-week user study at the beginning of the game design process. Gamification was then identified to be an effective way to improve patients' rehabilitation process, especially on enhancing exercise compliance and effectiveness due to its motivating, progress-tracking and goal-setting nature.

Besides the common features that gamification provides, based on our understanding of the unique characteristics of TKR patients, four critical features were identified to be implemented in the game to maximize its effectiveness:

- 1) **Customizable:** Despite having undergone the same operation, patients' abilities differ greatly based on multiple factors. Even for the same patient, knee performance through the day can be affected by pain and swelling. The developed game should direct patients to the most appropriate game level during each session to ensure exercise effectiveness.
- 2) **Dynamic:** Similar to most rehabilitation exercises, TKR rehabilitation exercises consist of basic and repetitive movements. To keep patients well engaged, game play should not be solely driven by the single-planar knee movement.
- 3) **Pain Distraction:** From the user study, pain from movements was identified as the most significant obstacle that patients face after TKR. One objective of this gamification includes distracting patients from possible pain or discomfort that is associated with performing rehabilitation exercises.
- 4) **Enhanced Volition:** Fredrickson and Kahneman [25]–[27] explain how human memory works using a psychological heuristic called “Peak-End Effect”. When people are asked to evaluate an experience, memory pieces of the peak and end moment of the experience are retrieved from their memory instead of the entire episode. Since

pain is the most unpleasant feeling during the exercises, it is cogent to assume that reducing the feeling at the point of peak pain (by pain distraction dynamics) and adding non pain-inflicting enjoyable game play at the end of the session would ameliorate the patient's memory of pain inflicted during the exercise. This would further enhance patient's compliance since they are more likely to make the decision to play again after a session with a more pleasant memory.

The following paragraphs illustrate a prototype built implementing the above mentioned features. The prototype employs one of the most common TKR rehabilitation exercises, the heel-slide. The heel-slide exercise aims to improve patients' knee bending movement. The patient is seated with a back support, legs straightened and relaxed on the bed as shown in Fig. 3. The patient slides his heel along the bed, towards his bottom, as far as possible, with toes and knees pointing upwards at the ceiling. He then straightens his knee to the starting position and repeats the action.



Fig. 3. Patient in a long-sitting position for the heel-slide.

The game prototype has been designed to be a 2D cartoon fishing game, developed using the Unity game engine for mobile platforms (iOS and Android). Mobile platforms provide good usability in such circumstances since users are able to freely adjust view position, distance and angle. Fig. 4 illustrates the game structure.

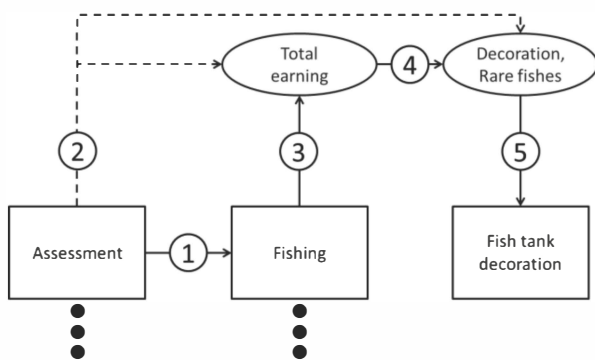


Fig. 4. Structure of the prototype. 1. Resources acquired for next stage. 2. Fortuitous rewards. 3. Earn from each successful attempt (exercise). 4. Exchange earnings for rewards. 5. Manage rewards for self-expression and satisfaction.

We break down the process of achieving desirable knee range of movement of the heel-slide after a successful rehabilitation session into recommendable progression stages, which defines the difficulty levels of the game. The developed

game consists of three stages: *assessment*, *fishing* and *fish tank*, described below.

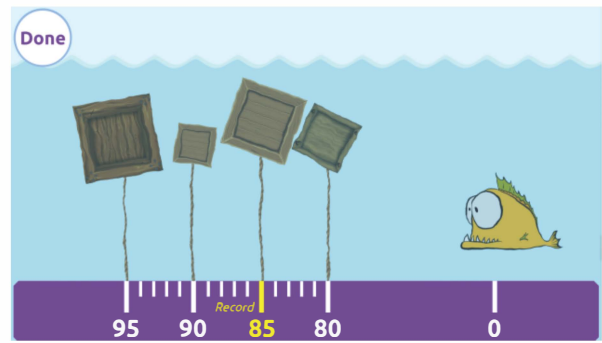


Fig. 5. Assessment session. An angle meter is at the bottom of the screen.

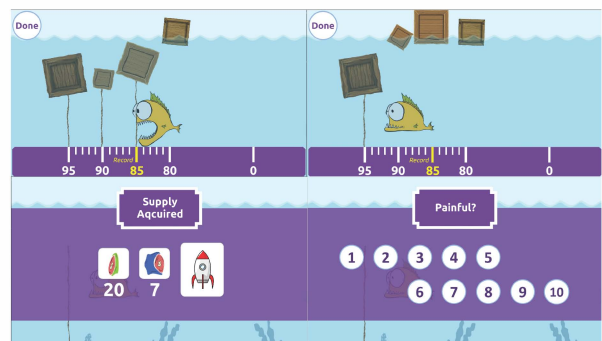


Fig. 6. Reward collection and pain registration.

**Assessment** (Fig. 5): Patients are required to go through an assessment session upon entering the game. This session is purposely designed to provide fun-enabling aesthetics such as curiosity and surprise. A meter at the bottom of the screen indicates the current knee angle. The knee range marked in yellow is the record of previous session. This ensures customizability as explained above.

During the assessment, the patient needs to perform a heel-slide. Crates are given after the patient logs in his knee range. The number of crates given will be proportional to the knee range the patient logged in. The crates contain resources for the next stage as well as fortuitous rewards that directly contribute to the ultimate goal of the game. The purpose of such a design is to encourage the patient to push his limit, to provide meaning for his suffering (due to pain) when doing so and to avoid developing antipathy towards the assessment.

The “Done” button on the top left corner brings up a reward collection and pain registration screen (Fig. 6) when pressed and brings the patient to the next stage.

**Fishing** (Fig. 7): Fishing is the main stage of the game where repetitive knee flexion exercises are performed. In order to keep the patient engaged, elements that demand decision making, resource management and ordering are implemented in this stage. Steps involved in completing the stage are presented in a sequential manner as follows:

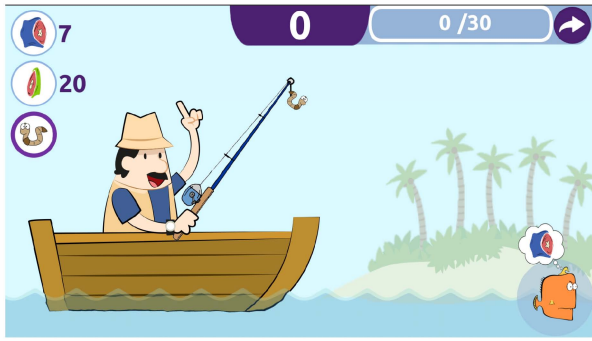


Fig. 7. Fishing screen. The left side of the screen shows the baits the player has acquired. The top bar presents current earning and progression. The bottom icon indicates the presence of a rare fish with its desired bait.

- 1) The patient decides which bait to use. Factors affecting the decision include: presences of a rare fish and its desired bait, the number of baits remaining, the type of fish to catch and luck (different fishes have different values; more than one rare fish may appear at the same time; using undesirable baits still grants a small chance of getting the fish).

Special baits, which are acquired upon completing the assessment stage, are not persistent and are erased after each session (except for the worm which is the default bait). This design is used to raise the imaginary value of the baits thus encouraging the patient to make each attempt count. This contributes to enhanced exercise compliance and effectiveness.

- 2) Once a bait is selected, the patient taps on the fisherman to trigger a bait throwing animation which brings the displayed screen into the water. The patient then drags the bait to entice the desired fish (Fig. 8). Fish falling within a bait's enticement range (dotted circle) will be attracted if the fish finds the bait desirable. Decision making is involved since different fishes demand different baits. Fishes have a number of behaviors to choose from, e.g., swim to the left, swim to the right or idle. The patient needs to avoid undesirable fishes when dragging the bait. Once a fish is enticed, the bait becomes static.

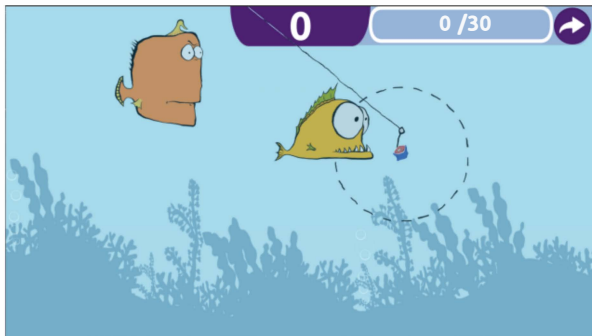


Fig. 8. Picking fish underwater.

- 3) The patient performs a heel-slide to draw the fish to the surface (Fig. 9). Once the fish takes the bait, the fish

will try to escape. The patient is given a limited time (represented by a decreasing progress bar) to complete a heel-slide to prevent the fish from escaping. If the patient is unable to complete the action on time, the fish escapes and the attempt is considered nullified.

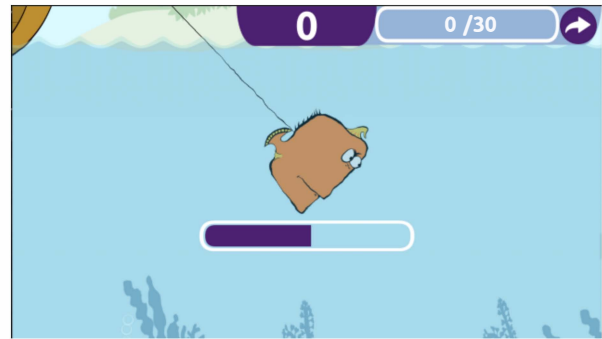


Fig. 9. Drawing the fish to the surface.

- 4) Upon successful completion of a heel-slide, i.e. when the patient's knee is bent to the maximum angle and pain is at its apex ("Peak" moment of the "Peak-End Effect"), pain distracting puzzles appear on the screen (Fig. 10). The difficulty of the puzzle is decided according to the registered pain level from the assessment stage, with a high level of pain leading to an easier puzzle and vice versa. A timer is displayed as a progress bar to indicate the remaining time the patient has to hold his knee. If the patient is able to complete the puzzle fast enough, extra rewards appear which can be collected for the remaining duration. This design aims to introduce more variables to the pain distracting puzzle and provide extra motivation for the patient to complete them.

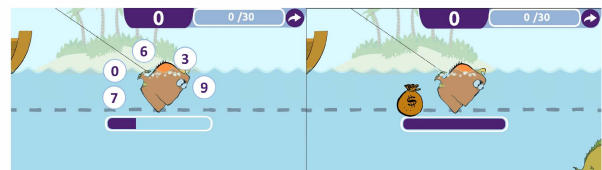


Fig. 10. Pain distracting puzzle and extra rewards.

If the patient does not solve the puzzle during the designated time or if the fish goes below the surface line (as a result of decreasing the knee angle), a fish escaping animation is triggered and this attempt is nullified.

The difficulty of fishing success has been carefully thought out and balanced. It is intended that besides correct completion of the exercise movement, the puzzle must be solved correctly in order to catch the fish and get rewards. This design aims to emphasize the importance of the puzzle in the patient's mind. Therefore, these pain distraction puzzles attract more attention from the patient and result in an enhanced pain distracting effect. After catching a fish successfully (Fig. 11), information about the fish caught is displayed and the patient is rewarded according to the attributes of the fish (size,



weight and rarity). This concludes a cycle of the fishing stage. This fishing cycle repeats as many times as required during a heel-slide exercise session.



Fig. 11. Fish information and score earned.

**Fish Tank** (Fig. 12): The fish tank is where the patient places fishes that have been successfully caught. Decorations can be acquired to create the desirable fish tank for each patient. This fish tank stage is introduced as the “End” moment of the “Peak-End Effect”. Knee movement is not required during this stage. The patient is expected to take his time to exchange earnings accumulated for rewards (decorations or display fishes) and manage them. The fish tank is designed to provide aesthetics values through self-expression, ownership and satisfaction to create an enjoyable ending of an exercise session.

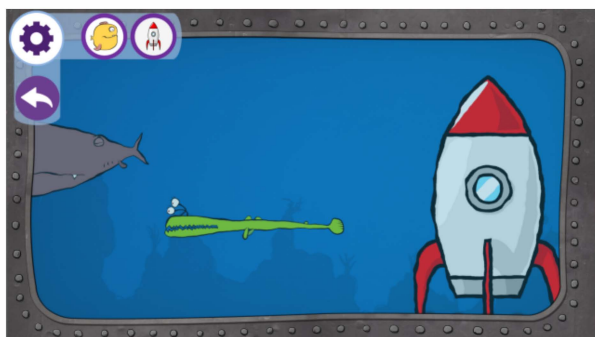


Fig. 12. Fish Tank.

## VI. PRELIMINARY RESULTS

As part of Fun-Knee™’s prototype development and refinement, we wanted to seek the feedback of physiotherapists in our institution. 26 registered physiotherapists who are practising in Tan Tock Seng hospital, Singapore, were involved in the feedback exercise. The conceptualisation and features of Fun-Knee™ was presented, and time for hands-on demonstration and trial was given to these physiotherapists, before a surgery was administered. These physiotherapists all work directly with TKR patients in either the inpatient (providing TKR rehabilitation in the acute postoperative phase) or outpatient (providing TKR rehabilitation post-hospital discharge) settings. Their years of practice ranged between 1 year to 17 years.

Physiotherapists rated Fun-Knee™ in 5 aspects: (a) hardware attributes, (b) software design, (c) usability, (d) clinical utility and (e) comparative effectiveness (relative to conventional TKR rehabilitation approach). A 5 point scale was used, with “5”: very satisfied, “4”: quite satisfied, “3”: more or less satisfied, “2”: not very satisfied, “1”: not satisfied.

a) Hardware attributes: Fun-Knee™’s prototype knee sleeve was rated for its physical dimensions and weight as shown in Fig. 13. Physiotherapists who rated “4” for dimensions suggested that the sensor units for the knee sleeve can be further shrunk so that its dimensions can appear more streamlined and sleek.

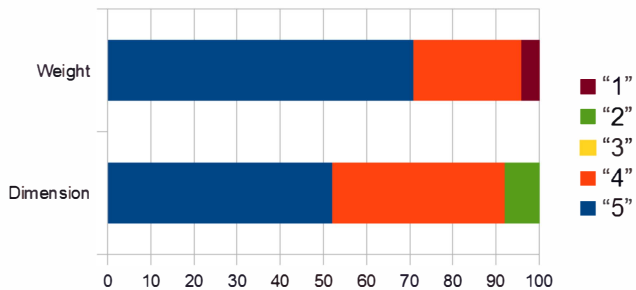


Fig. 13. Hardware Attributes.

b) Software design: Fun-Knee™’s software component was rated based on the “fishing” game that trains knee bending movement, as well as the prototype’s user interface. Majority of physiotherapists were impressed at this approach of “gamifying” exercises. Those who did not give a rating of “5” were concerned if patients’ interests could be sustained; as even gamified exercises may become routine after initial interest. A key concern for user interface attractiveness was having icons of sizes that are suitable for older adults to view and tap on. The results are shown in Fig. 14.

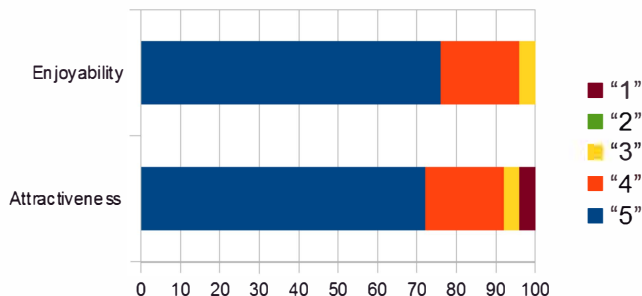


Fig. 14. Software Attributes.

c) Usability: Usability was divided into three sub-categories as shown in Fig. 15. Physiotherapists rated the physical comfort of wearing Fun-Knee™ and close to 60% found it very satisfactory. Other physiotherapists had reservations for whether the straps of the knee sleeve may overlap patients’ dressing and affect comfort. Over 20% of physiotherapists were concerned about Fun-Knee™’s ease of use. They suggested that we add in a Mandarin language option and make

the flow of gameplay and transitions more intuitive with cues e.g. blinking icons and glowing cursors. Majority of physiotherapists felt that older adults may take some time to put on and adjust the knee sleeve by themselves. While it was not too demanding, they were concerned that inaccurate placement of the sleeve and attached sensors may affect monitoring accuracy.

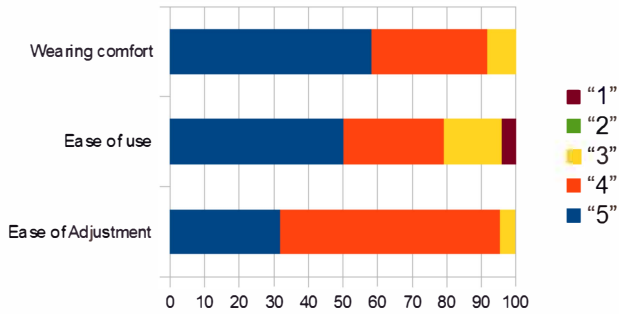


Fig. 15. Usability.

d) **Clinical Utility:** Based on their experience with TKR patients and the current healthcare system, physiotherapists were asked to rate Fun-Knee™ for its feasibility for being used in the existing TKR rehabilitation settings. The results, as shown in Fig. 16, indicate that over 65% of physiotherapists are confident that Fun-Knee™ can be implemented with minimal added demand or interruption in our current care structure. Slightly over 10% of physiotherapists do not think favourably of Fun-Knee™’s uptake, with concerns for additional time needed for patients to learn to use Fun-Knee™, and whether older adults are competent with smart phone usage.

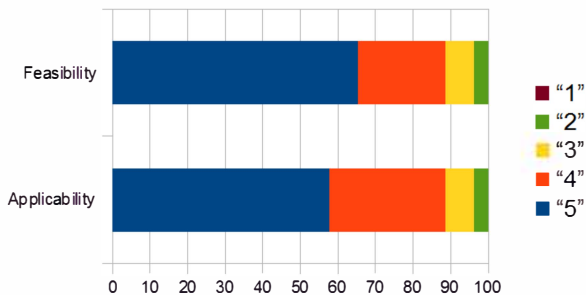


Fig. 16. Clinical Utility.

e) **Comparative Effectiveness of Fun-Knee™ in Addressing Current Clinical Problems:** Physiotherapists shared their perspectives on the ability of Fun-Knee™ to address the root causes contributing to sub-optimal rehabilitation, compared to conventional rehabilitation approach (use of exercise booklets and bedside teaching during hospitalization). Close to 90% of physiotherapists were confident that Fun-Knee™ would be more effective in boosting exercise compliance and effectiveness. About 20% of physiotherapists remain to be convinced that Fun-Knee™ can be a game-changer in improving care continuity between patient and healthcare system.

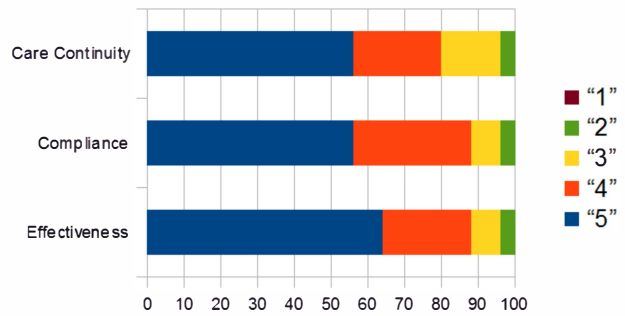


Fig. 17. Comparative Effectiveness.

Lastly, physiotherapists were given the open-ended question of listing what they perceive are crucial attributes of a successful rehabilitative innovation like Fun-Knee™. Each physiotherapist was asked to name three attributes and their input is summarised in Fig. 18. While we expected that physiotherapists would prioritize traits like “clinical accuracy” and “efficacy”, given their training as healthcare professionals, we were surprised to see “enjoyment” and “game design” most frequently listed, with “ease of use” and “safety” coming in next.

### 3 Most Important Attributes

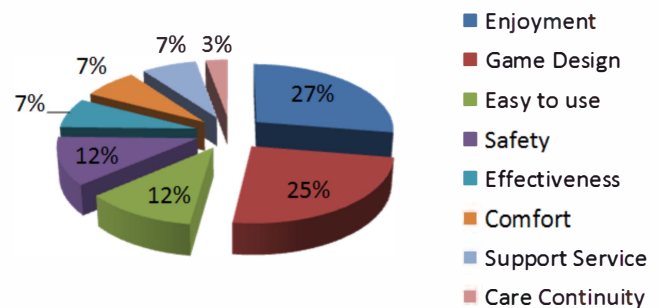


Fig. 18. Attributes importance.

## VII. CONCLUSION

In this paper, we presented Fun-Knee™, a novel sensor-equipped knee support paired with mobile device-supported games, specifically developed for Total Knee Replacement rehabilitation. The hardware component is composed of two inclinometers and a Bluetooth transmission module attached to a modified knee sleeve. The game component is realized with the Unity game design toolkit following the Human-Centered Design theory. Together, the hardware component serves as a “remote controller” to operate the mobile device, with a user’s leg, gamifying the TKR rehabilitation exercise. To evaluate the developed prototype, we have conducted a survey with 26 fully-registered, practicing physiotherapists. The great majority of them believe the developed system will



be clinically useful in terms of increasing care continuity, exercise compliance and overall effectiveness.

In future, we would like (1) to develop more games for other knee rehabilitation exercises, (2) to improve our hardware design to improve its usability, (3) to conduct clinical trials to validate Fun-Knee™'s clinical effectiveness and (4) to explore similar systems for rehabilitation exercises involving other body parts. This will help to translate our prototype into actual clinical use.

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