Force Feedback-Based Gamification: Squat Exergame Using Soft Actuators-Based Lower Limb Suit and Difficulty Adjustment Algorithms

(Force Feedback-Based Gamification：Pneumatic gel muscle (PGM) アクチュエーターベースの下肢スーツと難易度調整を使用したスクワット エクサーゲーム)

by

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List of Abbreviations

MCI	Mild cognitive impairment
VR	Virtual reality
AR	Augmented reality
MR	Mixed reality
QOL	Quality of life
DDA	Dynamic difficulty adjustment
STBLS	Short test battery locomotive syndrome
SWEs	Soft wearable exosuits
HBS	Home based settings
ACL	Anterior cruciate ligament
PCL	Posterior cruciate ligament
PAM	Pneumatic artificial muscle
PGM	Pneumatic gel muscle
PWM	Pulse width modulation
sEMG	Surface electromyography
vGRF	Vertical ground reaction force
SENIAM	Surface electromyography for the non-invasive assessment of muscles
MVC	Maximal voluntary contraction
HF	Hip flexion
KF	Knee flexion
HE	Hip extension
SPA	Soft pneumatic actuators
HMD	head mount display
MDA	Mechanics, Dynamics and Aesthetics

FSRs	Force sensing resistors
RM	repetition maximum
LR	Longitudinal rotation
CMRR	Common-mode rejection ratio
DOFs	Degrees of freedoms
DF	dorsiflexion
PF	Plantarflexion
PSQs	Parallel squats
FSQs	Full squats
KS	Knee shakiness
SD	Squat depth
KD	Knee distance
SW	Step width
FPA	Foot progression angle
COP	Center of pressure
COG	Center of gravity

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Chapter 1: Introduction

1.1 BACKGROUND AND MOTIVATION

The motions of the lower limb are essential for our daily activities such as running, jumping, walking, ascending or descending stairs, stretching our legs to engage in physical work and sitting or standing from a chair. The effective performance of these tasks is achieved through motor coordination of the different parts of the lower body such as ankles, knees and hip joints. Impaired motor coordination affects the speed and muscle power of the lower extremity. Therefore, the active functioning of the lower limbs or motor coordination is crucial for leading an independent and safe life. The coordination factor varies with age and increases the fall risks in the elderly population. The major factors affecting the performance of the lower limbs include work-related injuries, aging, lack of physical activity and certain medical conditions. Aging with the elderly population leads to decreased endurance capacity and loss of muscle strength resulting in further deterioration of physical health. It is also observed that there is ignorance of physical activity among younger people these days.

Moreover, the limitation of community activities causes individuals to become housebound and isolated from society, mainly those who are at their older ages and patients who suffer from minor motor problems. Therefore, the deceased cognitive conditions such as dementia and mild cognitive impairment (MCI) are becoming more serious with both older adults and healthy individuals. This would certainly affect physical and mental health for a long time. Accessibility to the hospitals is challenging where rehabilitation professionals are checking on the advanced technologies to improve both physical and mental health at one core. Integrating exercise activities with virtual reality (VR)-based gaming platforms would reinforce the prominent dependence on physical exercise and improve mental health. The introduction of exercise-based games is a motivational approach to dealing with physical and mental health disorders such as obesity, psychological stress, and other chronic ailments. A simplified version of user-centric designs of exergames would ensure the increased immersion level of users keeps the individual motivated and leads a healthy lifestyle.

The exercise-based gaming application has a significant effect that is not only limited to the medical field and rehabilitation science. The applications can be used in the entertainment industry and other related fields integrating more VR interfaces, mixed reality (MR) modules and augmented reality (AR) using actuators-based suits. The primary intention of this research is to develop an immersive training environment that induces the interest to be involved in regular physical activities. This will serve as a tool to promote a positive attitude towards motor learning and improving quality of life (QOL).

Increasing the core strength and proper posture maintenance is also a significant factor to consider in strength training activities. There are many cases where the users or patients suffer muscle dislocation or cramps while performing power physical training.

The novel application focuses on the following attributes in the different sections of the interface modules.

Exergames

- Adaptive home-based training which is useful to individuals in all age groups.
- Platform to enhance motivation improving physical and cognitive health.
- Contributes to empowering functional abilities in a wide range of fields like medical science, sports and entertainment which is beneficial for both clinical and non-clinical populations.
- Self-training platform that eliminates the need for therapists to perform instruction.
- Social engagement while including many players reducing isolation and loneliness.
- Introduction of dynamic difficulty adjustment (DDA) algorithm to motivate the users with greater immersion reducing the fatigue and stress conditions.

- Audio-combined visual feedback to intensify the task accomplishment.

Soft actuators-based lower suit

- Using force feedback to enhance dynamic difficulty protocol.
- Integration of force feedback and VR for ensuring effective performance of exergame training.
- Controlled force feedback providing both assistance and resistance based on the movement.

1.2 LITERATURE REVIEW

The increasing surge of the elderly population and the lack of motivation towards doing physical exercise shows a rising trend in the mobility disorders and chronic ailments [1]. All age groups depend on rehabilitation for any muscular disorders occurring due to the above reasons. However, the elderly face a higher percentage of locomotive disorders making them unfit to perform even their daily activities. There are many traditional assessment methods followed to test the severity of the mobility disorders such as short test battery locomotive syndrome (STBLS) [2].. However, the efficient reach of the physical rehabilitation techniques always depends on the use of advanced technologies increasing their attention and effort during the training [3, 4, 5]. They also depend on the factors such as intensity, orientation and duration of training which will enhance the rehabilitation for faster recovery and better treatment [6, 7]. These factors can be evaluated and improved through several cutting-edge technologies such as robotic systems and exercise-based games for providing effective results in physical rehabilitation and mental enhancement.

The robotics field has obtained a growing interest in recent years primarily with the exciting advances in various streams of medical sciences [8]. The researchers will develop various valuable applications ranging from manufacturing to safety and healthcare [9]. They mainly developed exoskeletons with rigid materials increasing the complexity for producing the forces/torques and proper motion for the rehabilitation techniques. The mechanical complexity influencing the weight and size of these structures makes it very challenging to create robotic technologies [10, 11]. Soft wearable exosuits (SWEs) help us overcome these limitations, therefore ensuring the development of the systems with safety, increased comfort and cost -effectiveness [12, 13, 14].

Besides the soft robotics, exergames have becoming an exciting and intensive rehabilitation technology reducing the burden for healthcare providers in terms of establishing repetitive training tasks [15]. The exergames support autonomous rehabilitation with home-based settings (HBS) eliminate the presence of therapists providing the motivational benefits with sustainable adaptation [16].

1.2.1 Exergame based training programs for the lower limbs

There are several exergaming applications that support the implementation of effective therapy with adaptive functions of exercise definition, virtual technique, game design and parameters introduced to increase motivation [17, 18]. Games and exercises together can address health issues like obesity, stress, weakness, and psychological conditions that are brought on by insufficient physical activity with the increasing aging status [19]. Exergames can create a positive effect improving the perception of physical activity and an individual's enthusiasm. There is notable research that relies most on the adaptation and adjustment to their skill level separating the gameplay elements for reducing the cognitive load and demand on the physical exercise [20, 21].

Adaptation compliance

Adaptation mechanisms are very crucial for matching the knowledge of the players attributes which helps in implementing more static conditions. This leads to preferable game types based on the training module and physical performance characteristics [22, 23]. Adaptive exergames supports the establishment of successful unsupervised training which is task-specific with subsequent muscle movement [24]. We can achieve better adaptation and independence through VR-based physical therapy (PT) which is more interactive, flexible, engaging, and portable [25]. Accuracy feedback ensures judgements whether the performance is overestimated or underestimated based on the knowledge got through the training in virtual environments. This eliminates the repetition of trials and increase of fatigue and stress during therapies [26].

Posture management

Proper posture maintenance minimizes the strain on the human body and primarily influences the performance of the motions. This also prevents damage or progressive deformations in all positions, including standing, lying down, sitting, squatting, etc. This study involves the assessment of the squat-based motions to raise the stability conditions of the lower limbs. Squatting techniques vary resulting on the user's strength which might lead to incorrect posture and repetitions of the squats [27]. Several types of research explain the different types of squat depths based on the anterior cruciate ligament (ACL) and posterior cruciate ligament (PCL) forces. This study recommends a broad perspective on the relationship between upper and lower limb kinematics (knee distance ≥ shoulder width) and unrestrained knee movements during squatting. The study [28] ensures the natural foot positioning method maximizes hamstring activation in both free and weighted squats. This technique could prevent the practices of half squats from being used during performance enhancements due to increased pain and discomfort after the training [29].

1.2.2 Soft-type wearable exosuits (SWEs)

The lower limb-based dexterous applications were very few compared to the upper limb dexterous training. A study proposes the orthosis survivor's rehabilitation system, especially in the ankle with the development of a soft wearable robot by Kwon et al. in 2019 [30]. The design is concerned with the bending motions of the ankle using the pneumatic artificial muscles (PAMs) to assist the dorsiflexion (DF) and plantar flexion (PF) motions. A similar article was proposed by Bae et al. in 2018 [31] that introduces a soft exosuit that assists DF and PF for the paretic ankle. The actuator block consists of 2-DOF-based driving motor unit with gear combinations. Hassan et al. in 2018 [32] proposed an EMS-based actuation model integrated with the force sensing resistors (FSR) fabricated as a shoe insole. Heel stepping is the motion considered and shows better results in coordinating the calf muscle group.

A powered orthosuit using a soft actuator for body weight support on the treadmill was developed which confirms the improvement in the stiffness of the hip and knee joints [33]. It is required to study the loading and unloading effects of the actuators and research proposes an experimental evaluation of the characteristics of the pneumatic actuator while developing a lower limb power suit [34]. A similar recent work used pneumatic gel muscles (PGMs) to detect the gait phase by assessing on the muscle activities of the lower limbs [35]. A perturbation-based study assessed the performance of the posture balance during standing through PGM-based upper limb exosuit reducing the postural impairments [36].

1.2.3 Haptic/force feedback

Haptic or force feedback is one of the most common interaction modes for skill enhancement in soft robotics. This feedback type explores the areas of force and touch sensation modalities through various actuators for both upper and lower extremities. The most common application includes human augmentation both in entertainment and medical field. Studies assessing the gait training with force feedback showed better improved performance in walking speed, muscle strength and persistence in stroke patients [37]. Vibrotactile and tactile feedback for gait interventions were utilized in haptic ankle bracelet [38] to evaluate the foot progression angle [FPA] and step width [SW]. The torque estimation system was developed with the movement of soccer pass by designing the lower limb force feedback suit to realize the performance using VR and force feedback system [39].

There are systems that completely depend on the force feedback to aid the phase detection of the gait cycle. The system was developed to provide assistance to hip flexion for reducing muscle impairments during the pre-swing phase of a gait cycle [40]. Force sensor resistors (FSRs) were utilized in visualizing the pressure mapping during compression therapy for the lower limbs. This evidence-based guidance provides a biomechanical force for pneumatic pressure control [41]. A similar work used FSRs to actuate PGMs in the augmented suit for the stand phase detection and identified the muscle unloading effects of the gait cycle [35, 42]. Force-feedback will enhance the skill and performance without compromising the comfort of the user.

Assessment techniques for force feedback-based system development

A. Studies utilized electromyography (EMG)-based evaluation

A comparative study investigates the muscle activation and kinematics with varying loads during the squat technique. Major lower limb muscles were targeted for squat with 30% - 100% of 1-repetition maximum (RM). This study is mainly performed to show the fact of gaining the same muscle activation pattern without heavy loads [70]. A similar conceptualization reports the effects of loading devices during two states of squat and lunge, targeting the sequential activation form of quadriceps and hamstring muscles [71]. Loaded (Smith machine) and unloaded (free weight) conditions of unilateral squats with different variables were studied to compare the kinematics [72]. This is mainly associated with gluteus maximus and vastus medialis muscles to estimate how it affects the calf muscles under distinct stability conditions. Consistency on muscular coherence was discussed by acquiring EMG signals and adapted to estimate synchronization in the vasti muscles by varying the electrode configurations during stable and unstable bipedal squats [73]. The study utilized sEMG signals to evaluate the performance of a Pneumatic Gel Muscles (PGM)-based wearable augmented suit for seven significant muscles in the lower limb with varying air pressure for gait phase detection [35]. Similar research enhances the performance of the PGM-based forearm glove to estimate the muscle force utilized during unloading and loading motion for senior adults with assisted constraints [74].

B. Studies utilized ground reaction force (GRF)-based evaluation

The research examines the joint forces and kinematics during the back squat exercise using the barbell to improve muscle power. This study suggested that greater vGRF was achieved with a significant increase in peak joint kinematics and gains 30%

of 1-RM [75]. Recent research has proposed the development of muscle power and strength through the analysis of vertical ground reaction forces (vGRF) with higher maximal values of velocities and accelerations. However, most of the research compares the GRF techniques for classification, resistance training and predication techniques [76] [77]. Hence, the demanding space for cross-correlation study with EMG is essential to understand the influence on the lower limb sEMG data.

1.2.4 Integration of exergames and soft-type wearable exosuits (SWEs)

There is always dependence on improving the motivation for daily physical activities. But there must be an inclusive factor that requires assisting the motions for training and rehabilitation. AR with exergames is showing an increasing trend of support assisting the motions. Older adults have a negative perception and less confidence in making an effort to do complex movements like squatting, one-leg standing, etc. The illusionary-based force feedback system proposed in [43] generated an imaginary movement through an immersive experience for training the lower limb muscles in the stair climbing situation. The stimuli from artificial muscles create force intensity, while the VR space provides the atmosphere of visual interaction with lower limbs for ascending the stairs. There are some recent studies that propose stealth adaptive exergame with autonomous training assistant and squat exergame focus on the real-time adaptation based on three important stability parameters: posture, pace and progression [44]. Extensive research on similar work using squat motions allows load adjustment by varying the number of actuators based on the user's risk level [45].

It is observed there are only limited works on integrating AR through augmented wearable exosuits (AWEs) and exergames for increasing the intensified training benefits for all age groups. To address the limitation, we have developed an exergaming platform introducing a difficulty adjustment module for eliminating the negative impact and increasing the motivation level of the users. This investigation focuses on posture control for reducing the risk of injuries by varying the stability parameters involved during the exergame training [46]. We will discuss the difficulty adjustment mechanism and the performance validation of the squat exergame in the following sections.

1.3 CONTENT SUMMARY

The literature section clarified the applications developed with the exergame concept which must rely primarily on adaptive compliance and posture management since the current study investigates these features and the influence of the features on the physical and cognitive profiles during the squat training. Then we discuss SWEs greatly involved in the lower limb dexterous training providing assistance for different types of motions. This is followed by the interaction mode: force feedback utilized through SWEs and finally the development of the SWEs integrated exergames for lower limb rehabilitation.

The study directed the development of the exergame to focus on the strengthening of the lower extremity through the squatting technique, which is the common motion recommended for power training regimes. Second, we advocate that proper posture control for squats affects the lower limb functions as explained in [27]. This estimation includes the comparison of the exergame-based deep squat to that of the difficulty-adjusted parallel squat while acquiring knee and physiological features during both interventions in the former study [46]. The current work estimates the performance utilizing time-controlled deep squats to that of the difficulty-adjusted parallel squat while acquiring knee features and muscle loading and unloading activities through electromyography (EMG). We have also proposed control strategies with an assessment of the EMG and ground reaction force (GRF) for actuating the soft pneumatic actuators (SPAs).

We classify this thesis into six chapters. The introduction chapter is followed by a system description that discusses the human lower limb anatomy, biomechanics and DOFs of lower limb functions involved while performing squat motions, exergame and its components, PGMs and their characteristics and control system to provide assistance and resistance from PGMs. The third chapter describes the method with the difficulty variation technique and the fourth chapter discusses the technical evaluation of the user studies performed with the improvised exergame module and EMG features. The conclusions from the user studies and prototype evaluations are then presented. The final chapter discusses the research's potential for future studies.

Chapter 2: System description

2.1 INTRODUCTION

This section contains a detailed description of the lower limb anatomy and squat biomechanics to actuate the PGMs. This discussion is followed by an explanation on the various degrees of freedom (DOFs) of the lower limbs supporting in performing squat motions. The exergaming module with related components and designing of the different sessions is also explained in detail. Finally, the overview of the design and development of the pneumatic actuators with force-pressure relationships and corresponding muscles actuated based on the assistance and resistance with the control system are also discussed.

2.2 THE HUMAN LOWER LIMB

The lower extremity of the human body is composed of the seven major segments of the hip, thigh, knee, leg, ankle, foot and toes and it is adapted to provide a stable yet mobile structure. There is a greater number of joints within the entire lower extremity allowing us to move over uneven spaces with varying speed and direction. It is evident that the lower limb always serves for locomotion. The leg is the crucial segment responsible for mobility, which is again classified for different motions of walking, running, jumping, squatting, kicking, climbing, etc. This section provides extensive information on the joints and associated muscles for performing the lower limb functions.

2.2.1 The anatomy of the lower limb

The lower limb originates from the hip joint which is the ball and socket joint responsible for the stable motion of the lower leg. Whereas the thigh portion joins the hip joint and knee joint to increase the stability function. The knee joint is the primary part considered in this study to determine the assessing parameters during the squat motions. The articulations of the ankle joint: talus, tibia and fibula bones connect the knee and ankle joint which is significant during ambulation. The hip and knee joints perform both flexion and extension while the ankle joint performs only flexion: dorsiflexion and plantar flexion.

Hip joint

The hip joint comprises the connection point where the hip combines with the trunk of the body. It is composed of two major bones: the thighbone or femur and the pelvis [47]. The hip works together to perform the major motions of flexion and extensions as shown in Figure 2.3 and secondary motions of abduction, adduction, circumduction, and rotation.

Flexion

Range of motion varies from 110°- 120°. There are three planes considered for all ranges of motions of the human body. They are sagittal, frontal and transverse planes as illustrated in Figure 2.1.

- The flexion happens in the sagittal plane around the transverse axis.
- The primary acting muscle responsible for the flexion is the iliopsoas, which is the largest muscle group. The other hip flexor muscles are the iliacus, Pectineus, Rectus Femoris (RF) and Sartorius [48] which is also represented in the Figure 2.2.

Extension

- Range of motion varies from 10°- 15°.
- The extension also happens in the sagittal plane around the transverse axis.
- The primary hip extensors are the Gluteus Maximus (GM) and the hamstrings represented in Figure 2.2. This powerful group of hip extensors is used for functional activities involving upward and forward propulsion of the body, such as jumping, running, stair climbing, and transitioning from sitting to standing [49].

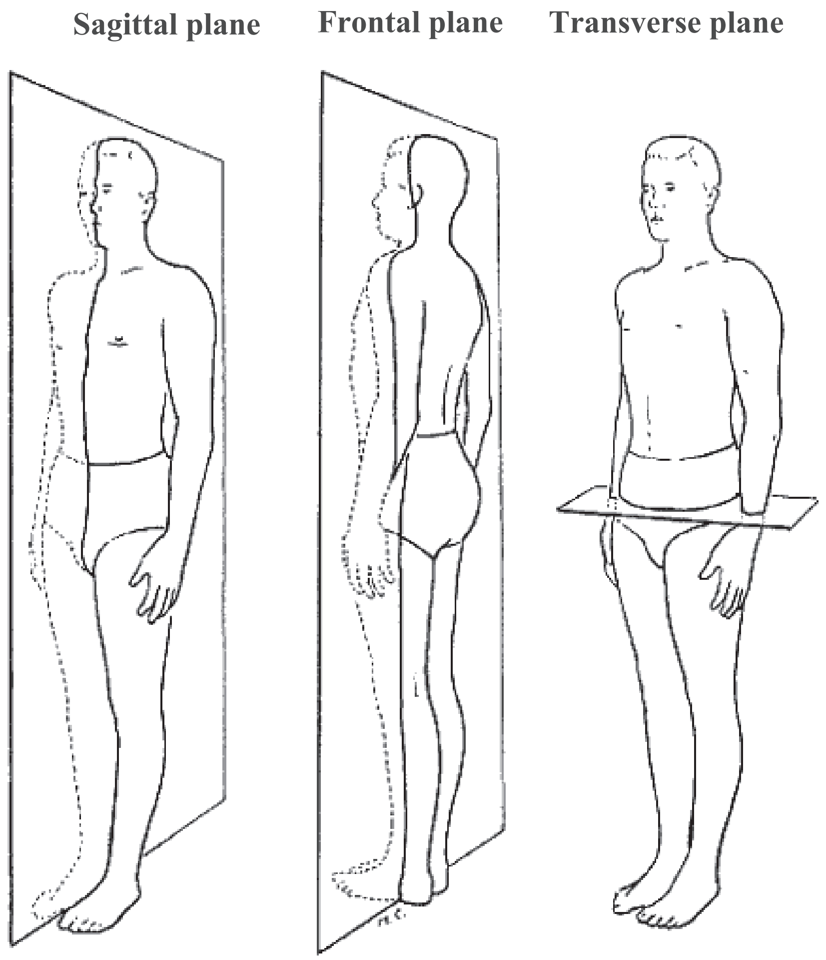


Figure 2.1 Anatomical planes to describe the DOFs and location of structures in human anatomy

Knee joint

The knee joint is a hinge-type synovial joint, which allows for flexion and extension (and a small degree of medial and lateral rotation). It is formed by articulations between the patella, femur and tibia. Knee range of motion (Knee ROM) should include an assessment of knee flexion and extension as shown in Figure 2.3 and tibial internal and external rotation [56]. The evaluation portion of this study primarily depends on the assessment of the knee joint features for analyzing the performance effect.

Flexion

- Range of motion varies from 0°- 140°.
- A variable flexion-extension (FE) axis perpendicular to the sagittal plane and a longitudinal rotation (LR) axis are thought to drive knee motion.

- The primary knee flexors are Semimembranosus, Semitendinosus, and Biceps Femoris (BF)—long and short heads represented in Figure 2.2 and Popliteus [57]. Many of these knee flexors also rotate the knee internally or externally.

Extension

- Range of motion varies from 0°- 15°.
- A variable flexion-extension (FE) axis perpendicular to the sagittal plane and a longitudinal rotation (LR) axis is thought to drive knee motion as shown in Figure 2.3.
- The four quadriceps muscle group of Vastus Intermedius (VI), Vastus Medialis (VM) and Vastus Lateralis (VL) which is represented in Figure 2.2 are three heads that arises from the femur while the fourth head Rectus Femoris (RF) that arises from the hip bone forms the major acting muscles for the knee extension motion. They make up the majority of the thigh and are one of the most powerful muscles in the body [58].
- Many activities, such as kicking, jumping, cycling, running, and basketball, rely on knee extensors.

Ankle joint

- The ankle joint (or talocrural joint) is a synovial joint located in the lower limb. It is formed by the bones of the leg (tibia and fibula) and the foot (talus).
- Functionally, it is a hinge-type joint, permitting dorsiflexion and plantar flexion of the foot.
- The ankle joint is formed by three bones: the tibia and fibula of the leg, and the talus of the foot.
- Plantar flexion and dorsiflexion are the main movements that occur at the ankle joint. Eversion and inversion are produced at the other joints of the foot, such as the subtalar joint.

- ✓ Plantar flexion – produced by the muscles in the posterior compartment of the leg (gastrocnemius, soleus, plantaris and posterior tibialis) as shown in Figure 2.3.
- ✓ Dorsiflexion – produced by the muscles in the anterior compartment of the leg (tibialis anterior, extensor hallucis longus and extensor digitorum longus) as shown in Figure 2.3.

2.2.2 Degrees of freedom during squat motion considered for the prototype

The lower limb exosuit was developed in such a way as to support the soft actuator-based assistance for hip and knee flexion and full-time resistance for hip extension which is shown in Figure 2.3. The study aims to develop a system that integrates a gaming environment and exercises for the purpose of maintaining the posture of the motion involved: from deep squats to parallel squats. The integration is further facilitated with the inclusion of a soft actuator-based lower limb suit to provide the difficulty variation depending on the ability of the user. Since the current study limits the focus on evaluating the postural control by acquiring the knee features, it is restricted to hip and knee flexion and hip extension and not the ankle DOFs. The details on the squat postures and depths will be described in the next section.

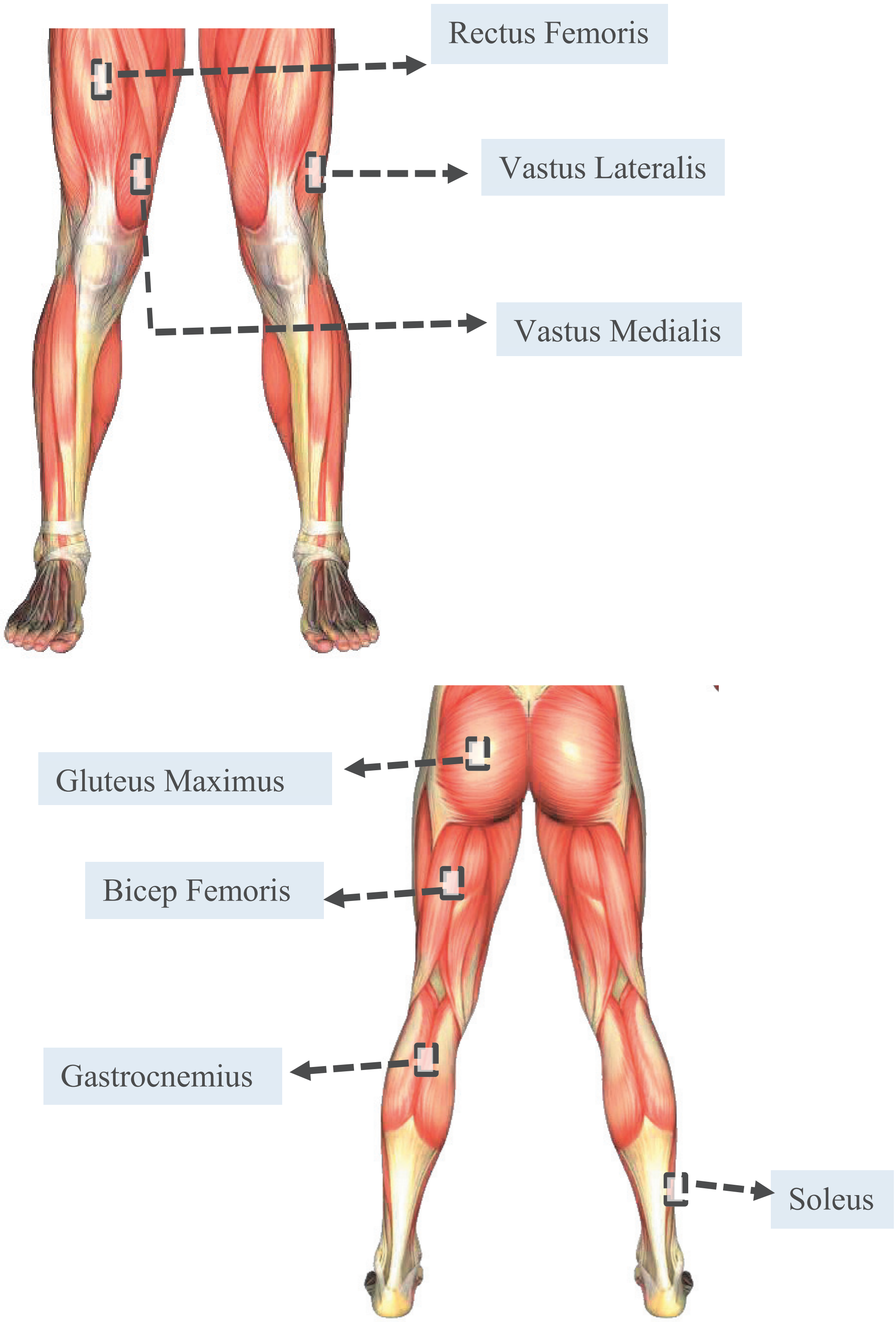


Figure. 2.2 Primary acting muscles of the lower extremity contribute for muscle activation during squatting motion

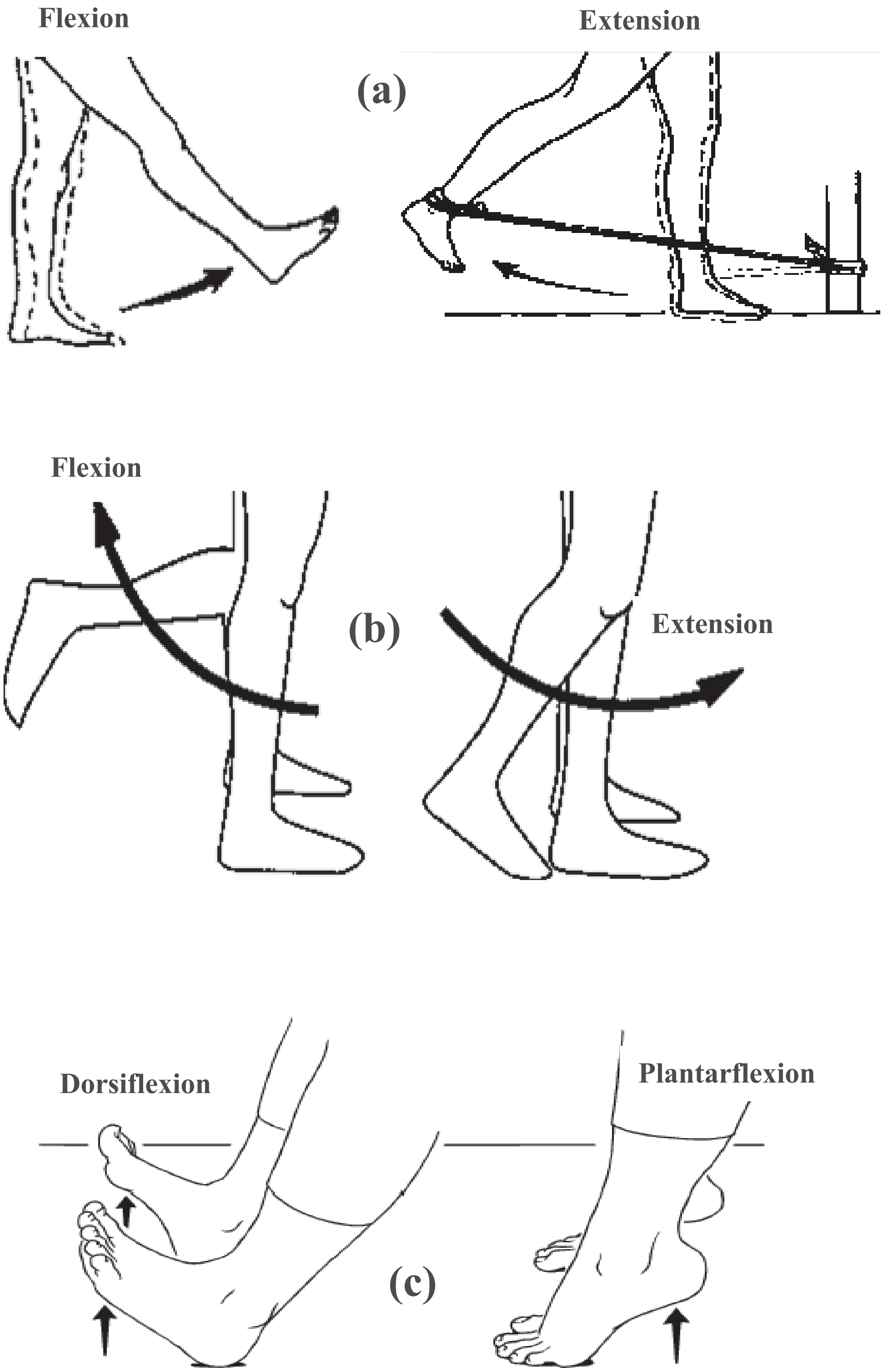


Figure 2.3 The DOFs - (a) hip joint, (b) knee joint and (c) ankle joint associated with the squatting movement for implementing exergame

2.2.3 Biomechanics of the squat cycle

The squats are multi-joint exercises where we bend our knees to proceed to the descending phase and maintain the position to acquire the squat phase and stand back to make up the ascending phase which is illustrated in Figure 2.4. Squats are considered an effective exercise pattern considered towards dynamic strengthening of the lower extremity. Squat motions help us to do daily tasks such as walking, climbing stairs, bending, or carrying heavy loads efficiently. In our study, we have considered free-weight squat exercise as the assigned task for the exergame protocol.

Squatting depth is one of the many technique variables that affect knee stress during the squat exercise. Squats can be executed at a variety of depths, which are typically determined by the knee's degree of flexion. Squats are frequently divided into three basic categories by strength coaches: partial squats (40° knee angle), half squats (70° - 100°), and deep squats (greater than 100°). The difference between the parallel squats (PSQ) and full squats (FSQ) is illustrated in Figure 2.5.

As we have mentioned, it is considered as a powerful training pattern for strengthening the lower limb muscles, it is required to understand the proper posture form to avoid the risk of back core and knee injuries. There is a high possibility of adverse effects when the incorrect set patterns of squat posture were followed for training programs [27]. In a recent study, resistance-trained men underwent prolonged squat exercises to investigate the neuromuscular and functional changes. According to the study, trained individuals should execute full and parallel squats to improve their strength and functional performance. Due to limitations in performance increases and increased pain and discomfort following training, the half-squat exercise was also discouraged [29]. There are kinetic works that detail the relationship between the Anterior cruciate ligament (ACL) and Posterior cruciate ligament (PCL) with varying depths of squats. The study investigated the stance with increases more compared to the should width; it defines the unrestricted expansion of the knees during squat [28].

There are studies that recommend limiting the range of squat depth to parallel while extremely deep squats will increase the force on the ACL and lead to knee displacement [59]. It is primarily prescribed to maintain the squat depth to reduce the risk of ACL injuries and fatigue which might result in long-term rehabilitation and bedridden situations [60]. For this purpose, we would like to propose a technique for proper maintenance of squat posture using a novel difficulty adjustment technique which will be described in chapter 3.

We will further describe the difference between deep and parallel squats, which is the main objective of this study. Deep squats result in greater activation of lower body musculature compared to parallel squats.

Half or parallel squats

The half squat is defined as squatting to knee angles of 40°- 45°.

In PSQ form, your thighs should parallel the floor during descent.

Significant benefits of this workout include greater knee stability, reduced risk of injuries and improving your overall mobility [61].

Full or deep squats

The full or deep squat describes squatting at knee angles of 80°-100°.

In FSQ form, the calves, and hamstrings touch while the hips are closer to the ground. Many fitness experts would advise against this routine as there are higher chances of injuries [62].

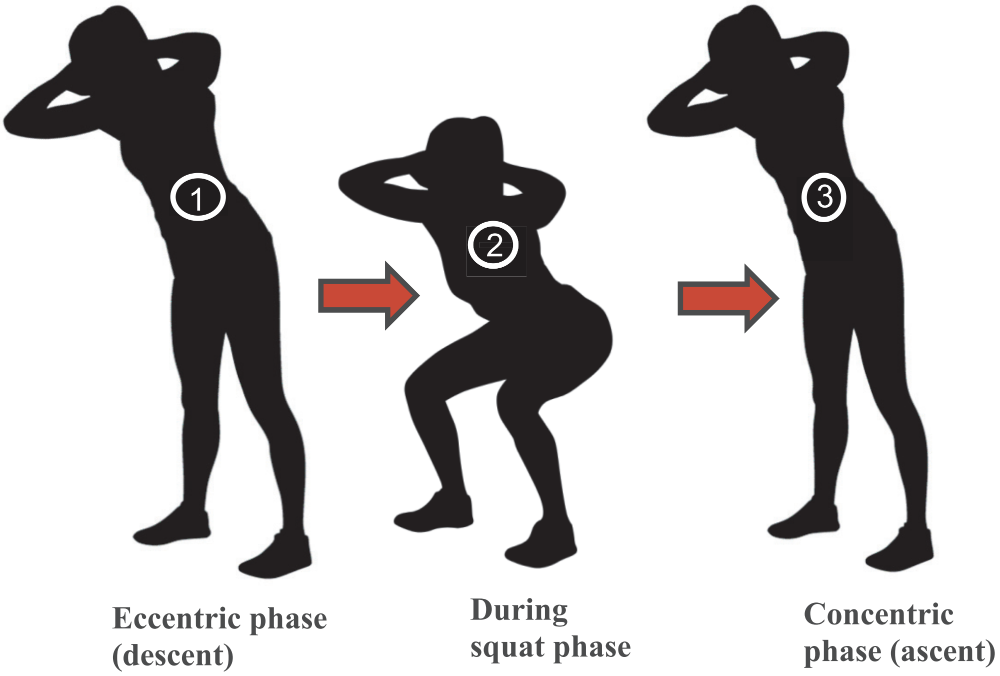


Figure 2.4 The three common phases of squatting technique

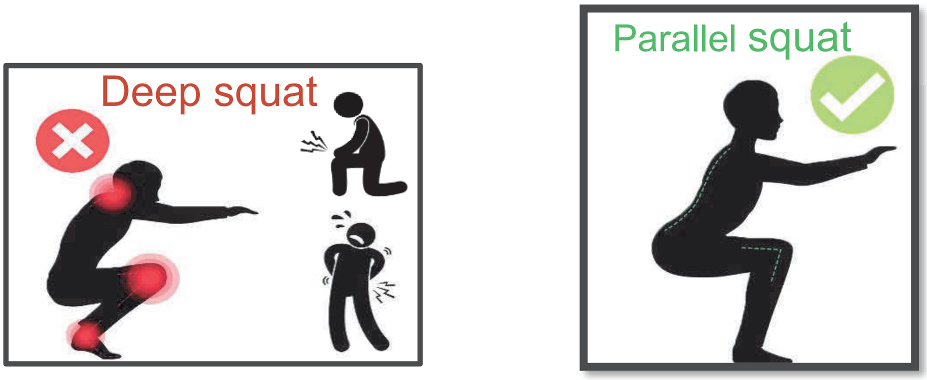


Figure 2.5 Posture difference between full or deep squats (FSQ) and parallel or half squats (PSQ)

2.3 EXERGAME EVOLUTION

Exergames are considered as a primary tool to interact with machines through purposeful body movements based on the game scenario developed with either VR or no VR platform. This offers the functional capabilities to stimulate physical and cognitive reactions based on repetitive task-oriented exercises. There are many situations that hinder mobility through locomotive disorders like locomotive syndrome (LS) [50]. Degeneration of the locomotive functions will have a negative impact on the population worldwide, leading to reduced life expectancy and the inability to have an independent life. LS is also caused due to the lack of lower extremity exercise on a constant basis [51].

Exercises like squats and lunges have been shown to lower the risk for this disorder and to promote mobility and general well-being in the elderly when practiced frequently along with diet and lifestyle adjustments [52]. Consequently, the global requirement for physical therapies and healthcare to treat mobility malfunctions has been observed to increase while the number of therapists and physicians is decreasing because of the demand [53].

To address the issues of lack of motivation and home-based exercise environment, social exclusion leading to musculoskeletal disorders, it is recommended to develop an evidence-based adaptive approach to gaming platforms with the inclusion of exercise modules. A wide range of exergames have been proposed for this purpose to optimize the different strategies of difficulty adjustment of gameplay with performance and motion limitations of the player. A study investigated that exergames can help seniors with their strength, balance, and other physical abilities, as well as other aspects of their health [54].

Exergames can have a positive impact on a person's mental motivation to exercise, which may help to improve compliance with recommended levels of physical activity over time. A further study indicated that frailty recovery can be done through the introduction of exergames among the elderly [19]. The comparative verification over conventional exercises was well explained with both mental and physical health outcomes in [55]. The other recent research where an event-driven solitaire exergame module in which gaming components needing mental activity were segregated from those requiring physical activity in order to lessen cognitive strain taking the preferences of the population into consideration [20].

A squat exercise game with varying loads dependent on the number of PGMs to actuate in accordance with the user's risk degree was implemented in the earlier work [45]. This restricts the load adjustment based on the amount of force used and the degree of difficulty during the session whenever assistance or resistance is needed. To get over the restrictions and control depth and posture when performing deep squats, we created this exercise game concept.

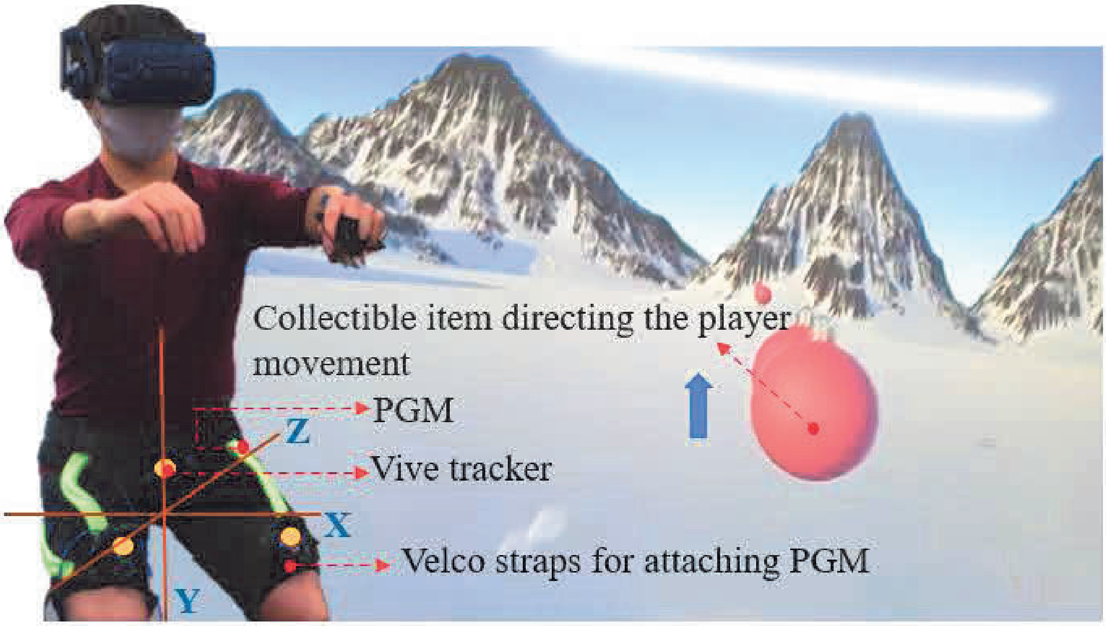


Figure 2.6 Exergame sample scene describing the components used and x, y and z includes the planes illustrated in Figure 2.1 contribute to calculate the user dimensions from the Vive trackers and HMD

2.3.1 Components used for exergame development

The HTC Vive ecosystem is used to create a VR environment for efficient human computer interface using UNITY software. There are two components involved in developing exergaming module for the study. They are as follows:

Vive head mount display (HMD)

The HMD serves as a virtual glass for providing both audio and visual feedback when providing training. The placement of the HMD (x_h, y_h, z_h) plays a significant role in defining the different phases of the squats as shown in Figure 2.6.

The user's dimensions were calculated from the calibrated values obtained with the help of both HMD and Vive trackers. The metrics used for detection are detailed below:

Idle: The user is standing still facing hands parallel to the ground.

Threshold range= (HMD position < torso threshold value)

Onset: The user is initiating the squatting movement by flexing the knees. Threshold range = (torso position > (left knee position − 0.15) and torso position < (left knee position + 0.15))

During squat: The user performs the parallel squat or deep squat.

Threshold range = ((HMD position < head threshold value and torso position > (left knee position − 0.15) and torso position < torso threshold value)

End: The user returns to the idle phase.

Threshold range = (HMD position > torso threshold value)

Vive trackers

The Vive trackers were used to monitor the movement of lower extremity joints. The placements were based on the three axial points of sagittal (x), transverse (y), and frontal axes (z) as shown in Figure 2.1. The knee trackers were attached just above both knees: left knee (x_{lk}, y_{lk}, z_{lk}), right knee (x_{rk}, y_{rk}, z_{rk}) and the torso tracker (x_t, y_t, z_t) was placed above the abdomen. There is a separate gaming personal computer connected with the big screen monitor was used to develop effective interaction and acquisition of the assessing parameters. The trackers were attached with firm supporters to avoid the detaching of trackers during the training when squat intensity is heavy while performing deep squats which is shown in Figure 2.6.

2.3.2 Designing of exergaming sessions

The novel conditions of exergaming sessions introduced in this research was based on the five-detection metrics described in Figure 2.7.

The user attempts to start with the idle phase of the parallel squat when the calibration is done with the user dimensions measuring the height of the user to that of the ground.

During the onset phase, the user will start doing the initial descent when the collectible object appears on the screen depending on the calibrated values adjusting the user's height to that of the collecting object's height.

During squat phase, the user attempts to collect the objects appears on the path in the VR space. The user can collect these objects only when they do the proper parallel squat. The user will hold here for 2 secs as items will be in a pair makes the user to maintain the parallel squat position.

During the end phase, the user will start doing the initial ascent when the collect objects disappear after collision or collection is done. This is confirmed with the scores and squat counts visible to the user on the top of the VR screen.

Finally, the user will come back to the idle position completing the collection of the objects and full parallel squat motion. This squat-inducing approach may help to eliminate differences in squat depth. Excessively deep squats may increase the risk of knee damage [59].

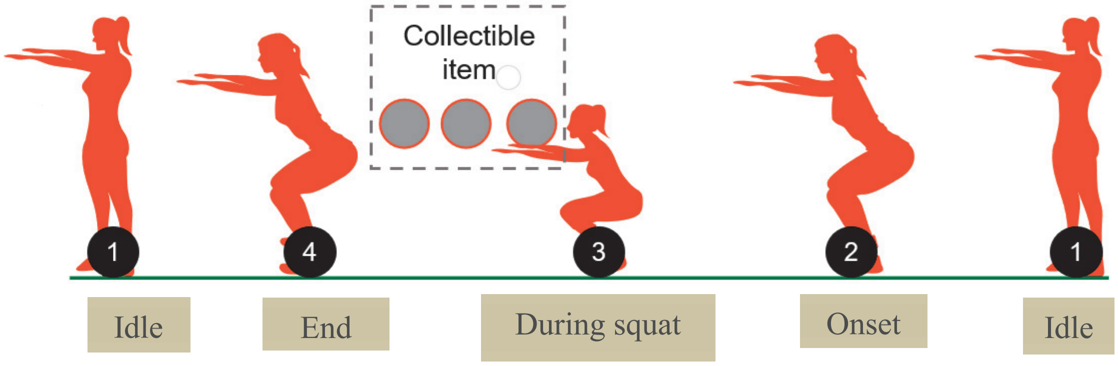


Figure 2.7 Distinct technical phases of squats considered for developing Unity algorithm to design the exergame condition involved

2.4 PNEUMATIC GEL MUSCLES (PGMS)

2.4.1 Overview

The PGM is a pneumatic actuator developed to be operated with a minimal compressed air range of 0.05 MPa to 0.3 MPa by DAIYA industries, Japan. The internal structure includes a soft tube made of a specific material: a styrene-based thermoplastic elastomer as shown in Figure 2.9 to increase flexibility and is externally guarded by a plastic mesh [34]. Compared with the conventional McKibben pneumatic artificial muscles (PAM) which is shown in Figure 2.8 demands a large quantity of air pressure to provide higher force, the soft nature of the inner tube in the PGM requires only the lower volume of input air pressure as minimum of 0.1MPa to produce forces of up to 40N [34] as shown in Figure 2.10 where with 0.5kg weight it provides high volume of force. This force is determined by the length of the PGM as well as the input air pressure. Thus, makes it a more suitable option for developing augmented motion-assist and resist suits because of its flexibility and soft nature.

Summarise the literature review and discuss the implications from the literature for your study – the theoretical framework for your study. Here you can make an explicit statement of the hypotheses, propositions or research questions and how they are derived from existing theory and literature. Establish from the literature (or gap in the literature) the need for this study and the likelihood of obtaining meaningful, relevant, and significant results. Outline any conceptual or substantive assumptions, the rationale and the theoretical framework for the study. Explain the relationships among variables or comparisons, and issues to be considered. This section should demonstrate the contribution of the research to the field and be stated in a way that leads to the methodology.

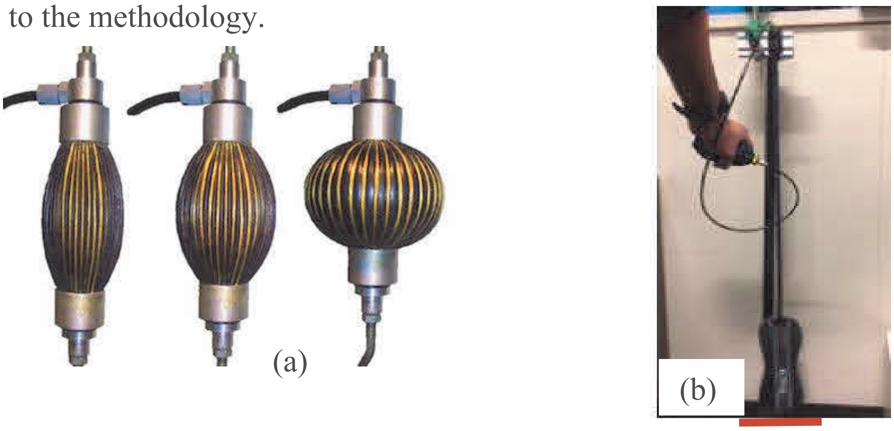


Figure 2.8 (a) Conventional McKibben PAM and (b) Elongation characteristics when 0.5kg weight attached with 30cm length PAM [78]

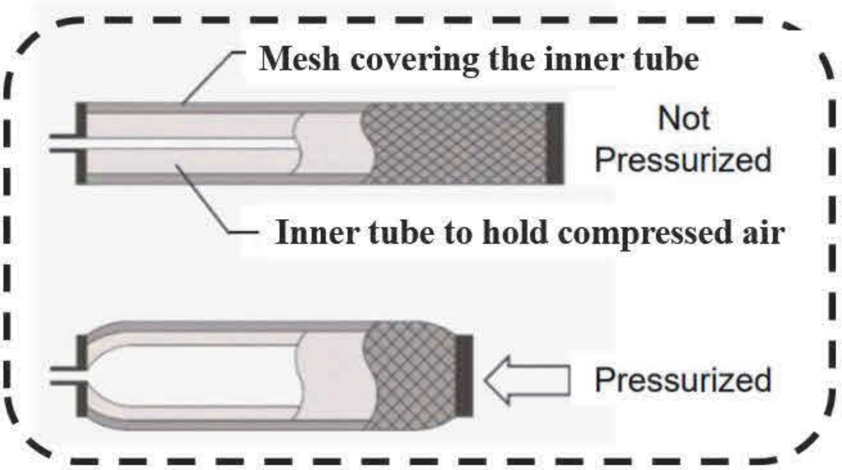
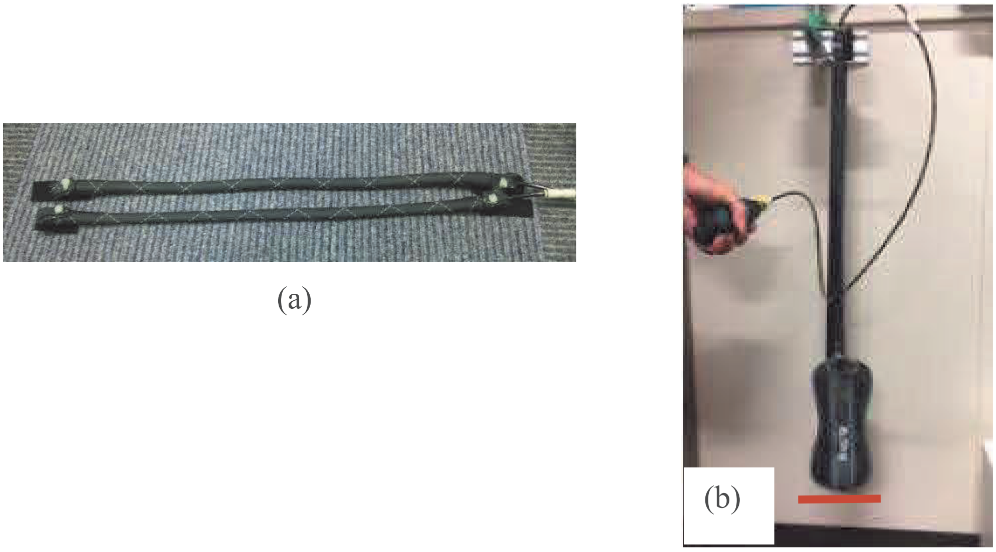


Figure 2.9 Working concept and internal characteristics of PGM



(a)

Figure 2.10 (a) External form of PGM and (b) Elongation characteristics when 0.5kg weight attached with 30cm length PGM

2.4.2 PGM force measurement

The PGM can deliver a specific amount of torque to two sides of the lower extremity joints when the upper and lower ends are attached to the appropriate joint counterparts. Figure 2.11 represents the force generation characteristics influenced by the air pressure change for the maximum stretched length modelled with the experimental setup in [34]. Previous research [34] shows that PGM can generate higher force than PM-RF10, a widely available soft artificial muscle equivalent as shown in Figure 2.12. PGMs have the advantage of being able to operate for longer periods of time while employing portable CO2 canisters as a supply of compressed air. We can observe that both contraction and elongation ratios for PGM show better outcome when compared to PM-RF 10.

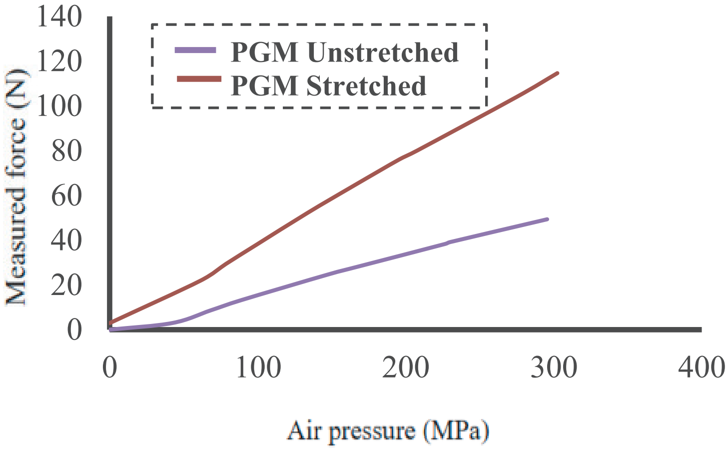


Figure 2.11 Force-air pressure relationship obtained in stretched and unstretched conditions of PGMs

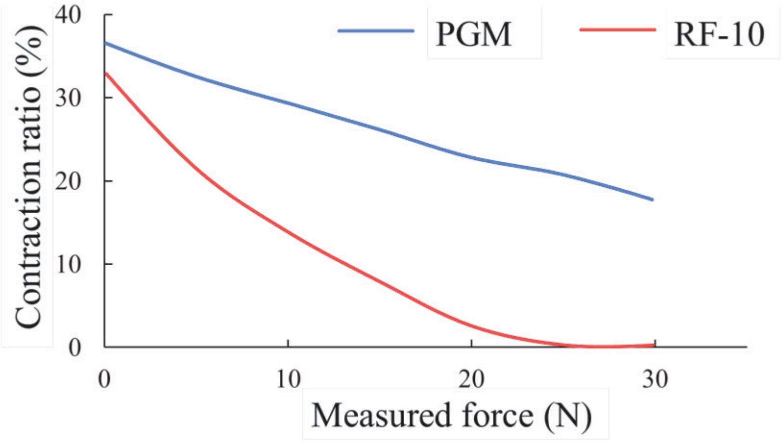


Figure 2.12 Relationship between contraction ratio and force with comparison on conventional RF – 10 and PGMs

2.4.3 PGM placements and corresponding muscles in the lower limbs for performing squat motion

In this investigation, we used three different pairs of PGMs as mentioned in Figure 2.13. Each set has two PGMs attached to each leg and 4 PGMS for each pair. The hip flexion (HF) pair is connected parallel to the rectus femoris (RF), vastus medialis (VM) and vastus lateralis (VL) muscles. The hip extension (HE) pair is connected similarly to the biceps femoris (BF) muscle, and the knee flexion (KF) pair is connected parallel to the gluteus maximus (GM) muscle. One end of the PGM is sealed, while the other end is connected with a plastic tube to acquire air pressure optimization from the control segment. The PGMs were fixed onto the Velcro-based straps, ensuring more stable attachment throughout the session without detaching even when more force was applied.

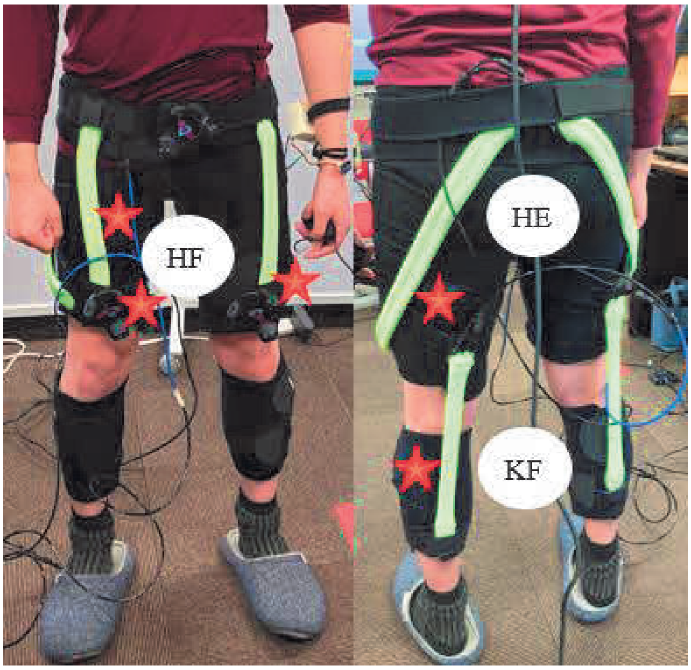
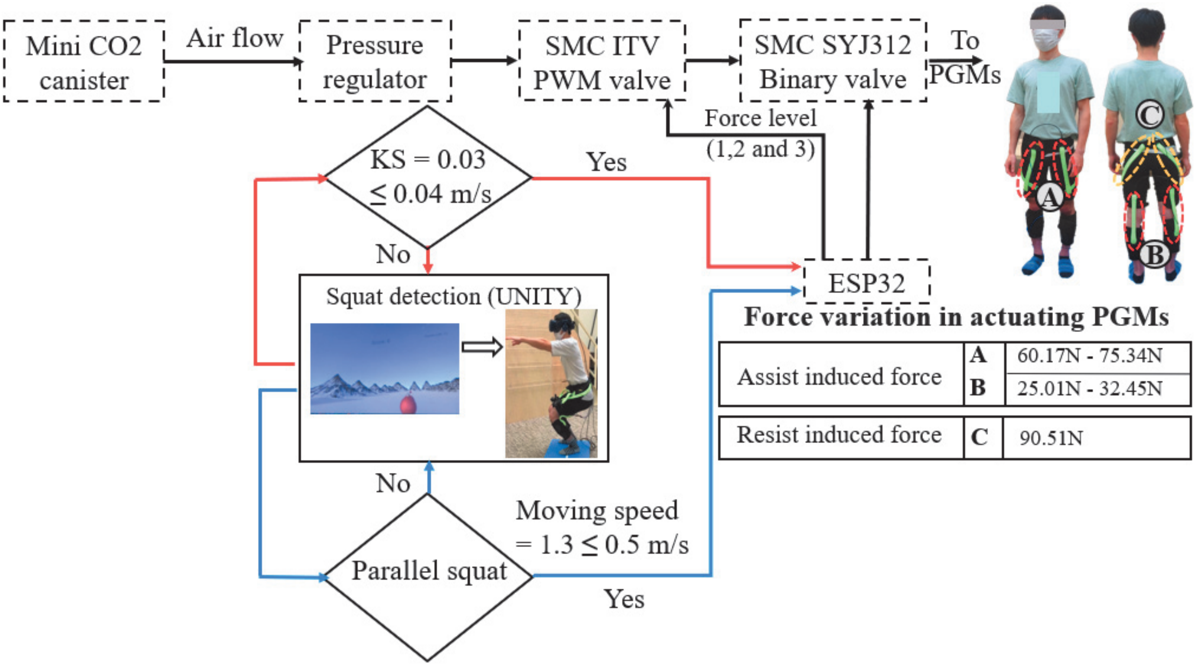


Figure 2.13 Positioning of PGM in the lower limb and EMG sensors illustrated with stars for the squat exergame training

2.5 CONTROL SYSTEM FOR PGM ACTUATION



Force variation in actuating PGMs

Assist induced force	A	60.17N - 75.34N
	B	25.01N - 32.45N
Resist induced force	C	90.51N

Figure 2.14 Assist – Resist control segment to activate pneumatic actuators for exergame sessions

The PGMs utilized in the lower limb suit are inflated using the control provided from the components illustrated in Figure 2.14. The mini -CO_2 air tanks are used to supply controlled compressed air which was developed by NTG Ltd. Industries, Japan. A pressure regulator linked to a canister supplies 0.05 MPa of steady air pressure. The PWM valve from SMC (ITV0031-2L) was used in the study to optimize the air pressure range required to activate the PGMs. Furthermore, the binary valves contribute to a distinct air pressure supply for assistance and resistance. The PGM pairs KF and HF shown in Figure 2.13 provide necessary force for knee flexion and hip flexion movements, whereas the remaining PGM pairs HE shown in Figure 2.13 provide resistance force for improving hip extension. The ESP32 microprocessor initiates digital control signals for actuation and de-actuation.

Knee Shakiness (KS) was measured via online data streaming from knee Vive trackers. If the KS was found to be within a specified range (≥ 0.03 m/s), PGM assistance was provided. During this time, the pulse width modulation (PWM) valve provides optimized air pressure. Whenever PGM-based resistance was required, it was delivered by the resist binary valve. Regardless of KS, the end of a squat phase was recognized. The linear polynomial equation denoted in the study [42] helps determine the resultant force acquired during the PGM actuation.

2.6 DISCUSSION

We built a static air pressure control system with the commercially available control components of PWM valves, solenoid valves, ESP32 and other air pressure supply materials. The exergaming components are very reliable in providing audio and visual feedback for concentrating on the game involved. However, the prototype has some limitations of dynamic control with PGM inflation and bulkiness of the prototype with exergame modules. To address these issues, it is required to develop a wearable satisfying the integration of dynamic control and lesser weight.

2.7 CONCLUSION

This section described the anatomy of the human lower limb and the purpose of considering the posture control technique to differentiate between the deep squat and parallel squat in the squat biomechanics section. We have also explained the exergame components and their utilization in designing the exergame conditions based on the different phases of squats. Finally, the PGMs and effective static control section to actuate the PGMs were described in detail.

Chapter 3: Methodology

3.1 INTRODUCTION

This letter focuses on the unique design of the exergame model, which enhances the healthy functioning of the lower extremities through squat motion. The developed study recognizes several aspects of implementing the DDA concept to achieve proper squat posture and depth to reduce muscle damage and estimate muscle strength in different squatting patterns. It also helps in improving the performance of the user in accomplishing the task with increased motivation throughout the session. The KS parameter determines the condition for dynamic difficulty optimization.

This section will describe the novel methodology followed by the difficulty optimization technique called DDA.

3.2 DYNAMIC DIFFICULTY ADJUSTMENT (DDA)

3.2.1 Overview

Dynamic Difficulty Adjustment (DDA) is the technique through which a game adapts its level of challenge to fit the skill level of the player. However, the impact of DDA on games has gotten conflicting reactions, with some claiming that it can both improve and degrade user experience. We dynamically adjust two factors in the game based on knee shakiness. The movement speed and the degree of assistance supplied by the PGMs to perform hip and knee flexion during the start phase of a squat are the adjusted parameters. PGMs are flexible, lightweight pneumatic actuators that can function at extremely low air pressure [34]. We control PGM assistance via a PWM valve, which controls the force produced by PGM actuation.

Adjusting the game difficulty based on the user's performance allows for more motivation to finish the gameplay. Any individual can develop a negative attitude if there is no optimization and challenges to progress the given task. As a result, it is critical to create balanced difficulties for players by altering the game parameters, attempting to provide appropriate hindrances to the player. In our study, we regularly tracked each participant's average KS. We optimized two game aspects based on this parameter to change the difficulty level. The first factor was the virtual environment's movement speed. This speed could be used to change the frequency of squats. The magnitude of assistive force (in Newtons) provided by the hip and knee flexion assistance PGMs was the second parameter.

The significance of introducing DDA is to balance a game so that a player remains engaged and inspired to keep playing. This allows for the simultaneous adaptation of both cognitive and physical challenges of the exergame. The assistance offered by PGMs was measured according to difficulty levels ranging with three parameters of KS, movement speed and induced force illustrated in control block diagram of Fig. Throughout the gaming session, a fixed resistance was delivered.

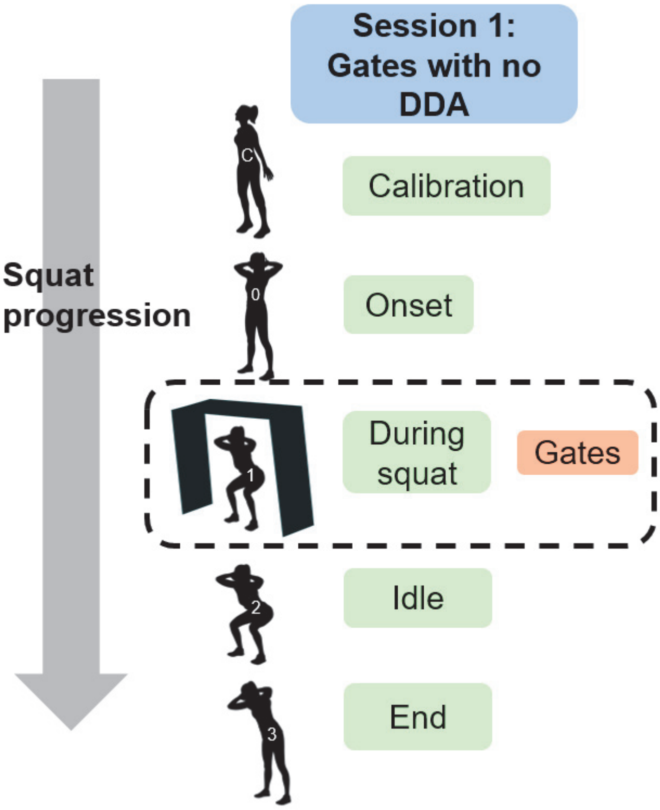
3.2.2 Research involved in implementing DDA and its effects

Outline There are several ways to increase the enjoyment and motivation during exercise-based games by tailoring the game difficulty manually according to the user's abilities. Manual adjustment is accurate but causes interruptions with the game flow. It is recommended to automatically adopt the difficulty variations through dynamic mechanism implementing in-game scores, counts on the training motions involved. Thus, it makes the adaptation of easy evaluation and interpretable indicator of perceived game difficulty.

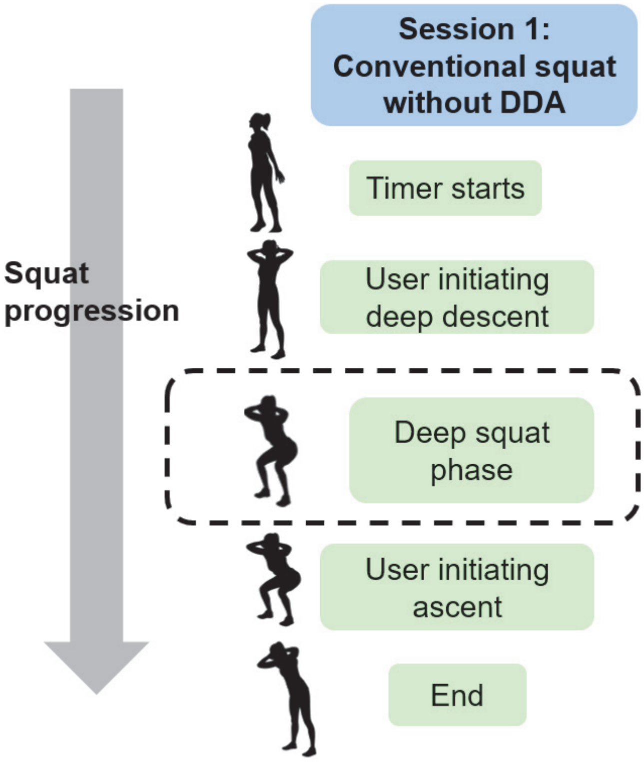
The study [63] describes the handling of MDA (Mechanics, Dynamics and Aesthetics) framework with continuous process of trial-and-error method. The DDA method monitors the exchange of inventory items to focus on producer-consumer relationships. The other work proposed an exergame [64] with optimized difficulty levels. This study shows that incorporating dynamically changed difficulty variables into a game increases the overall experience of the participants. Novel research [65] proved that Electroencephalography (EEG) based DDA can be used to identify both positive and negative motions evaluating only the cognitive benefits. This assessment can be used to enhance mental behaviors in treating the persons with psychological disorders.

Artificial Intelligence (AI) techniques are also used for producing dynamic balancing dealing with difficulty variations. AI usage allows us to predict the appropriate challenge level and increase player interest by enhancing either increased or decreased difficulty. In that way, an evolutionary based algorithm was introduced to ensure the change in difficulty for a robotic rehabilitation system in [66]. Similar work [68] with AI-DDA was employed to improve the efficiency of two simulated computer-controlled players by increasing competitiveness and efficiency. The players' strength was increased to 100%. This effort was made with seriousness. Transform@ is a game that promotes entrepreneurship skills.

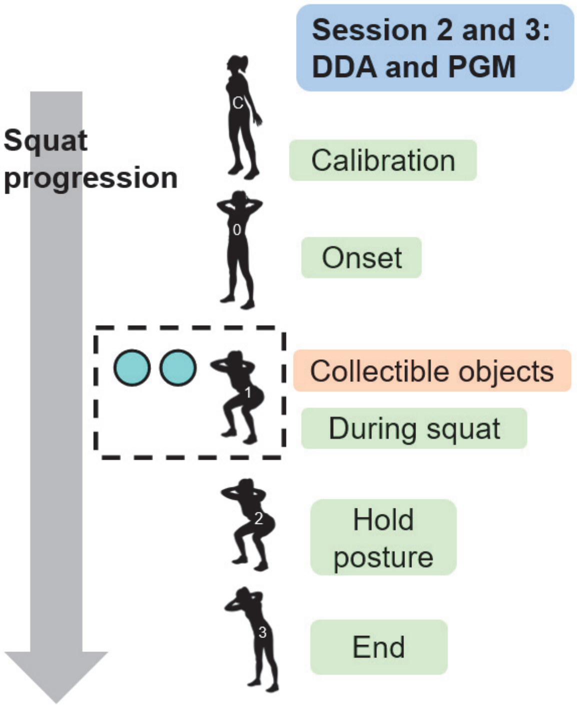
A gaming module reported in the study [67] evolves DDA algorithm for post stroke therapeutic visits considering incremental and random difficulty adaptation with three versions of Prehab systems. The distinguished illustration was explained in Figure 3.1 between the pilot study and the extended work of the squat exergame study.



Exergame with gates implemented in the previous related work of Ramin et.al in [44].



Time controlled deep squat implemented in the recent work [69]



Exergame sessions involving DDA and PGM used in the works of [46] and [69].

Figure 3.1 Difference between the pilot study and extensive study of squat exergame

3.3 DISCUSSION

DDA in exergames is a dynamic and ongoing process and is important to ensure that the game promotes proper squatting form to prevent injuries. We have considered the evaluation of the knee features by manipulating the movement speed and force applied to the PGM. The features considered are squat depth, knee distance and knee shakiness. However, there are. limitations of not taking into account the assessment on the foot position, back position balance and stability, count on the level of difficulty applied, and hip mobility, etc. We are planning to consider these parameters to efficiently promote the proper squat form, reduce the risk of injury, and optimize the workout experience.

3.4 CONCLUSION

This section describes the methods of implementing dynamic difficulty adaptation with the features considering only the lower limb performance and maintenance of squat posture during exergames. The detailed description on the evaluation of the acquired parameters for the two case studies done with the conventional and exergame based squats were presented in the chapter 4.

Chapter 4: System evaluation

4.1 INTRODUCTION

Technical assessment is mandatory for the iterative and research-based development process of any system. A holistic exergame design approach can achieve an attractive and effective training experience by considering the levels of body, controller, and game scenario. The feasibility or usability extent can be approved by the user only when it undergoes systematic evaluation. As a result, we performed the analysis on the knee features and physiological parameters to verify the squat motion intensity and posture control while estimating the cognitive condition. We have also tested the muscle unloading effects during squatting for various muscles of the lower limbs with the incorporation of DDA technique with squat exergame.

4.2 STUDY 1: PROPOSING CONTROL STRATEGIES WITH GRF AND EMG FEATURES

Understanding the relationships between load over the lower extremity muscles and the implications of strength training is vital in examining force-velocity and muscle activity controls. Consequently, this evaluation is essential for resistance training, frequently suggested to improve muscle power. Several studies explore muscle activity differences and determine the load intensity for employing appropriate muscles in strength training activities. The following subsections discusses the EMG and GRF-based assessment enhancing the muscle exertion and stability conditions for various postures.

This investigation was done to assess muscular activity and vGRF changes during squat motion. Also, to propose control strategies for actuating the soft wearable suits through setting the human kinetic (reactive forces) and muscular activity (sEMG) influencing the development of the core in the lower limbs.

4.2.1 Prototype evolution

1) Surface electromyography (sEMG)

EMG signals were acquired using 8-channel dual-mode portable EMG and physiological signal data acquisition system (Trigno wireless sensors synchronize through Trigno base station, Delsys Inc., Boston, MA, USA). The common-mode rejection ratio (CMRR) was fixed at 80 dB and the input voltage was set at 9 VDC with 0.7 A while 4370sa/sec was the set maximum sampling frequency. We have considered collecting EMG data from seven major muscles: rectus femoris (RF), soleus (SOL), gluteus maximus (GM), hamstring (HAM), and gastrocnemius (GA). as depicted in Figure 2.2. In order to lower the electrical resistance, the skin's surface was removed from the electrode attachment places by shaving and wiping with alcoholic wipes. Each muscle evaluated on the participant's right (dominant side) of the body had Trigno wireless sensors (41205 mm) affixed (Table 4.1). For the purpose of anticipating the signal detection, the sensor points are coated in 99.9% pure silver material, extending for about 10mm long, and spaced 10mm apart.

2) Force plate integration

Force plates developed by BERTEC solutions were used to measure foot pressure data with the anterior displacement of the subject's COP during each exercise. The subjects were instructed to take a posture on the force plate-integrated treadmill. After determining how far apart their feet should be for a comfortable squat, pressure readings at 1000Hz were collected.

Table 4.1 Muscles of interest for squat motion evaluation and electrode attachment positions

Muscles	Electrode placement in the lower limb
Vastus lateralis	two-thirds of the way along the anterior side of the thigh from the greater trochanter
Vastus medialis	30% of the way down the medial side of the thigh starts from the anterior iliac spine and about 3 cm lateral to the erector spine
Rectus femoris	At the middle of the anterior thigh, between the patella and the lateral inferior iliac spine.
Gluteus maximus	50% along the axis between the greater trochanter and the sacral vertebrae. This location correlates with the highest prominence of the centre of the buttocks, which is much above the apparent bulge of the greater trochanter
Hamstring	On the posterior region of the thigh between the ischial tuberosity to the femur
Gastrocnemius	Posterior part of the lower leg muscle runs from the knees to the heel along with soleus muscles
Soleus	Muscle located below the knees and runs deeper into the gastrocnemius muscles

4.2.2 Participants and user study

Three healthy men with an average age of 23 ± 2 years, weighing 56.5 ± 2.5 kg and an average height of 169.7 ± 6.7 cm volunteered to take part in the study. The exclusion criteria for recruitment include records of severe neuro-musculoskeletal problems, history of injury and surgery, fractures in the lower limbs, and recent discomfort in the lower limb. Two days before the trial, the volunteers were asked to refrain from engaging in strenuous physical activity. The users were required to complete an informed consent form before participating. According to the ethical guidelines outlined in the Declaration of Helsinki, the user study was carried out.

The study consists of three sessions and a sample test was given to assess their performance as the users were not familiar with the squat motion. Since the squats were not taken into account for their ADL, a pretest is always necessary. They were found to be able to perform successive squats without any interruption or any pain. A second preliminary step was completed to attach the Trigno wireless sEMG sensors on the corresponding muscles of VL, RF, GM, GA, SOL, HAM and VM in the lower limbs. After the EMG electrode placement, the main trial consisting of ten squats for each session was initiated. The study counts for 30 squats with a 2-minute break at the end of each session. Each session lasts for about 45 minutes. The maximum voluntary contraction (MVC) was measured during the main trial in accordance with the methods outlined in [79]. The MVC trials were recorded for each muscle group in a randomized order. A sufficient interval was provided between each trial. The subjects were asked to stand on the force plate during the trials, which is instrumented with treadmills manufactured by BERTEC solutions. All sessions were internally sampled at 1000Hz for calculating the vGRF and moments to determine the COP [80].

4.2.3 Results

The EMG signals were processed simultaneously from the first squat repetition using the EMG Works Analysis software. To demonstrate the 100% of the squat cycle, the processed s-EMG data were reduced to 100 points, where (0- 30%) represents eccentric activity, (31-60%) represents load at maximal activity, and (61-100%) represents concentric activity. The initial and final descent were defined as (0-14) % and (15-30) % respectively, while the middle phase of (31-60) % remains fixed with load at the peak phase.

The initial and final concentric activity was defined as (61- 80) % and (81-100) % respectively. In order to determine the mean-normalized EMG values, the raw EMG signals were sorted and filtered (passband: 3, response: band pass, corner F1:10 Hz, corner F2:500 Hz), analysed, incorporated (root mean square (window length: 0.100, window overlap: 0.08, remove offset)), and normalized to the user’s highest corresponding MVC trial. The normalized data were then smoothed using a moving average filter in MATLAB software 9.12.0 (R2022a). The mean and standard deviations were presented throughout the letter, which is analysed through repeated average measures for all subjects performing each trial.

The results of the muscle activity (%MVC) to the 100% squat cycle were illustrated in result figures. The dotted line indicates the first two phases of squat posture and initial descent from 0% and final ascent at 100%. This study utilized a controlled squat (parallel form) in which the gesture is restricted to 90 degrees of knee flexion. The load at the peak phase was considered to identify the maximum internal load exerted by the user. During this phase from 31% - 60%, the muscles VM and VL showed greater muscle activity compared to the other muscles. The insertion point connecting the vasti muscles and quadriceps tendon gets more load at the knee points. This phase could be a crucial finding in optimizing the load parameters of actuator based soft exosuit during the rehabilitation and strength training programs.

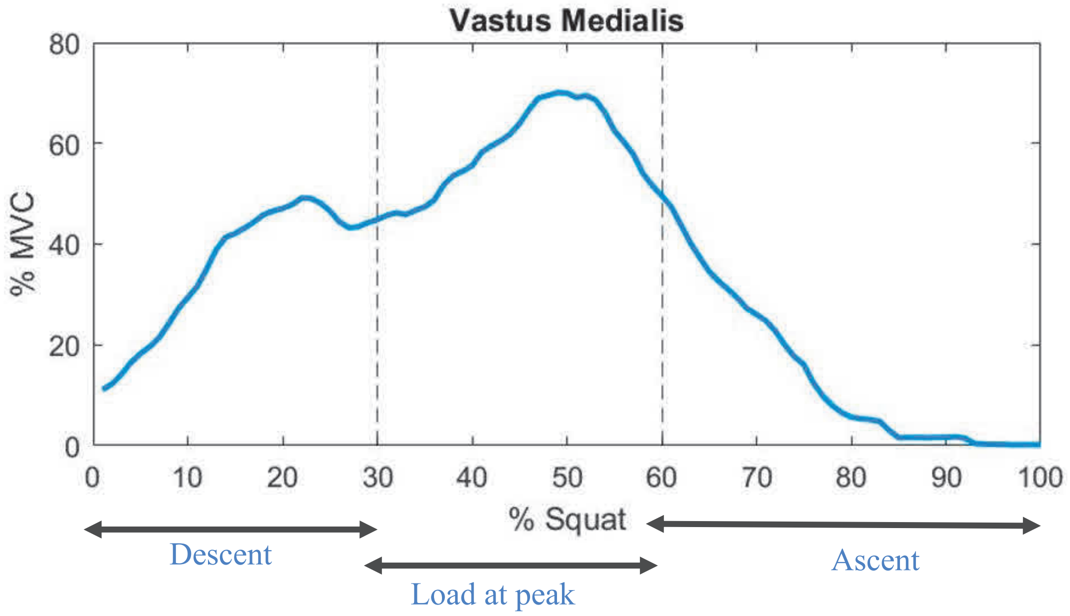


Figure 4.1 Maximum Averaged EMG activity of VM muscles for one squat cycle. Data were normalized to %MVC

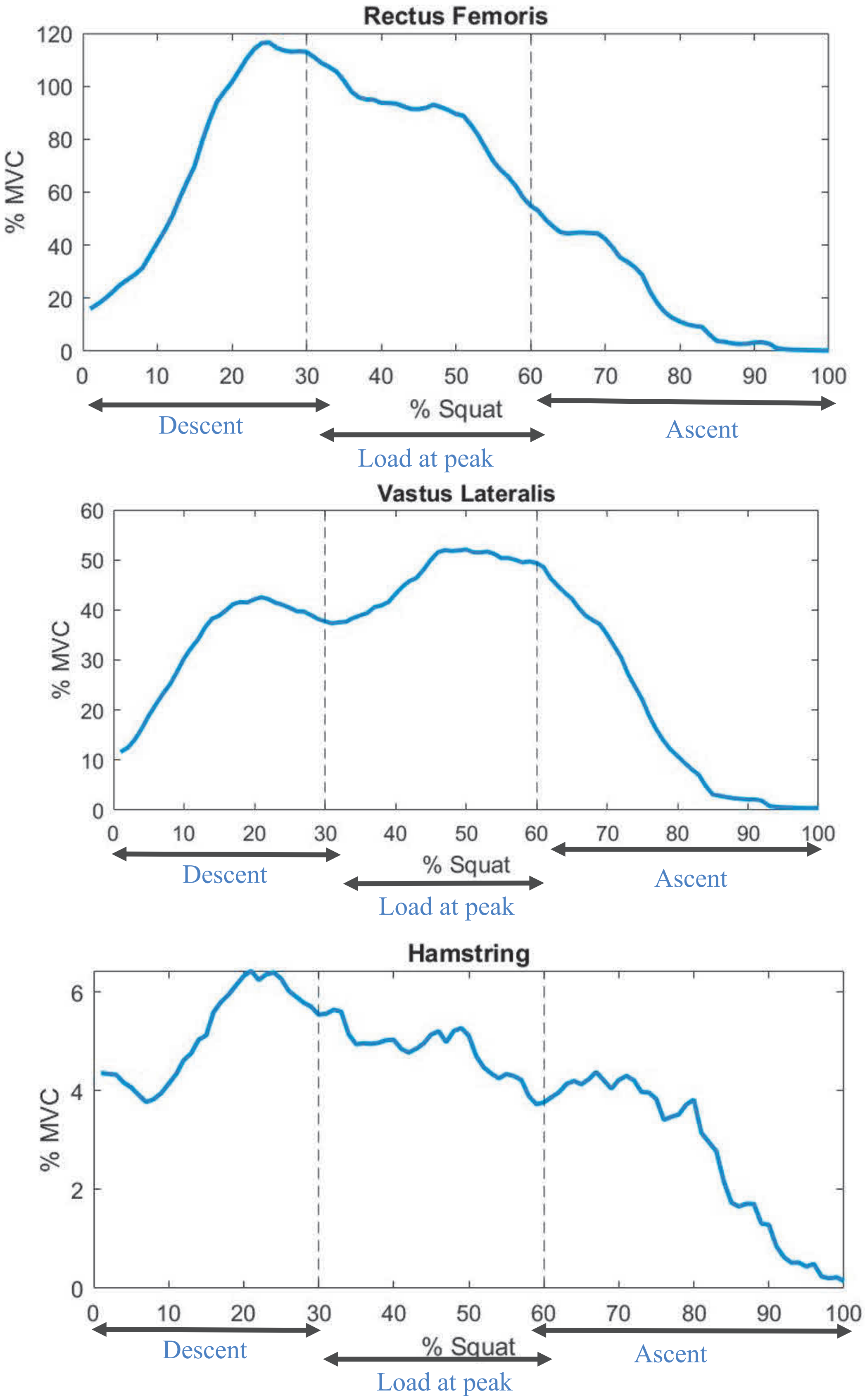


Figure 4.2 Maximum Averaged EMG activity of RF

VL and BF or hamstrings muscles for one squat cycle. Data were normalized to %MVC

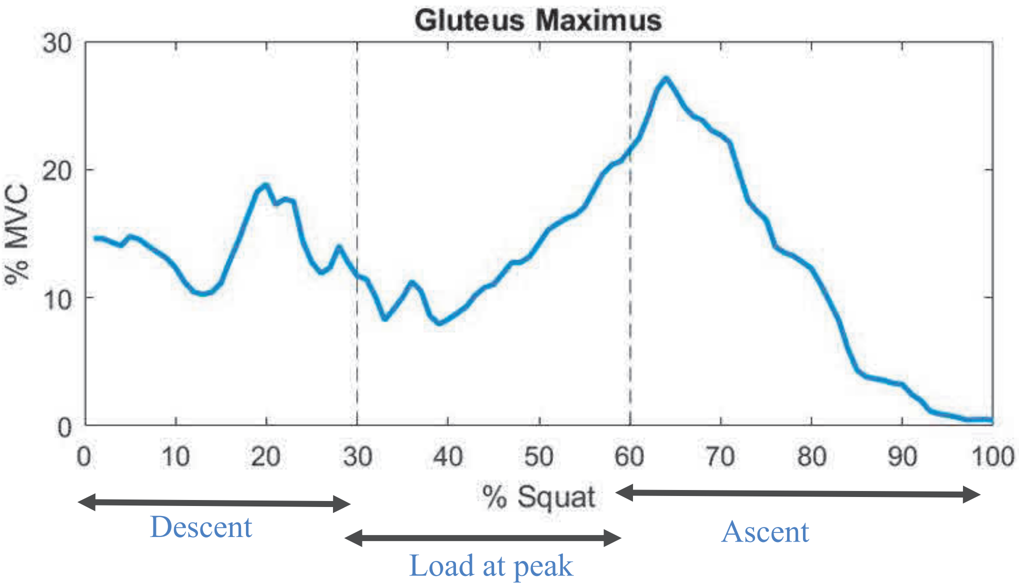
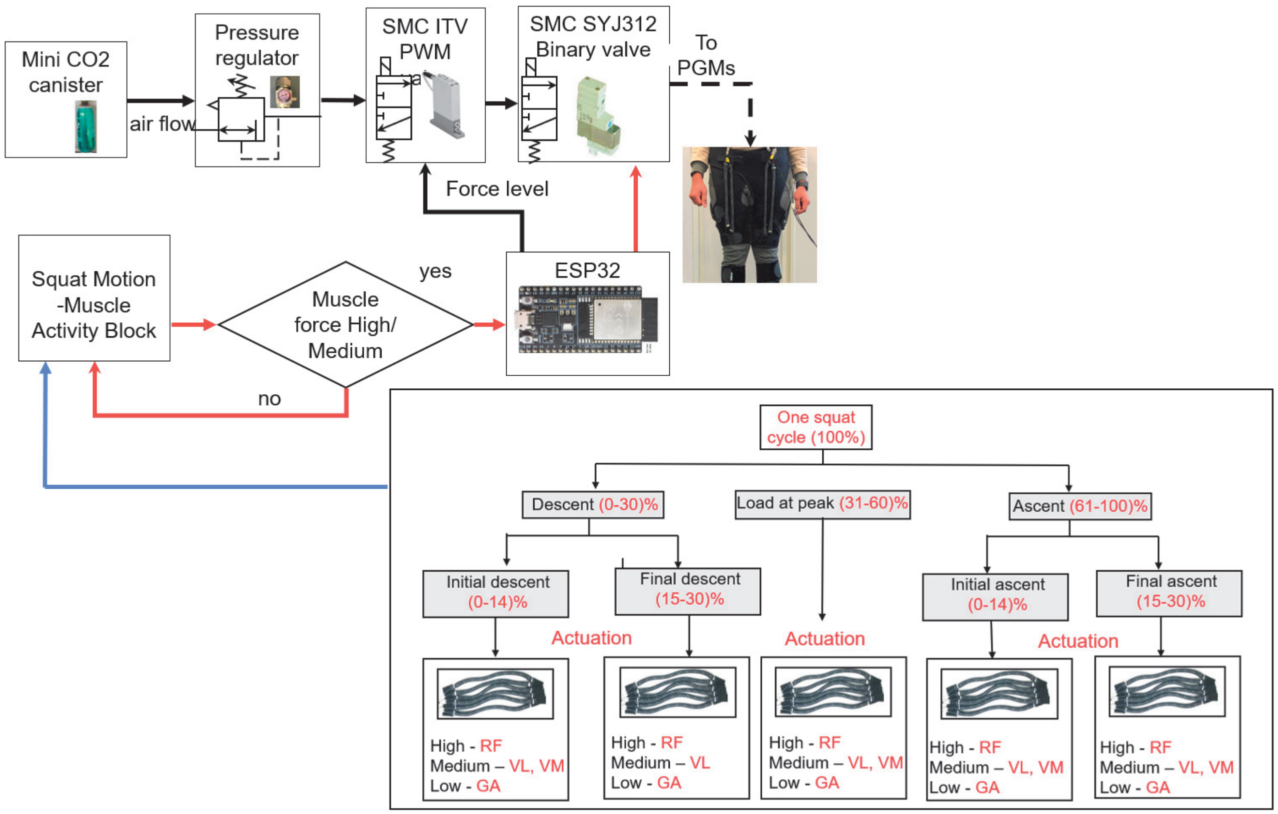


Figure 4.3 Maximum Averaged EMG activity of GM muscles for one squat cycle. Data were normalized to %MVC

The motion patterns of the lower extremities are greatly influenced by the ground reaction force. This clarifies the mechanical actuation during dynamic squat motion. In this study, vGRF is considered as the significant profile to comprehend the correlation between the sEMG waveforms. The study enables us to use vGRF data and sEMG to activate the soft exosuit system based on the state of the squat. From Figure 4.6, it is shown that the vGRF has a high correlation to sEMG and it could be used for controlling the soft exosuit in addition to several muscular activities.

Figure 4.4 Control flow with the proposed technique for driving the soft actuators in the future



4.2.4 Discussion

The current work discusses the possible kinetic and muscular activity variations during three different phases of the squat as shown in Figure 4.6. We aimed to see how these variations could support the load parameter optimization in soft robotics where the term load includes the pressure for actuation and control signals were based on sEMG or vGRF. The proposed control block is detailed in Figure 4.4. The muscle activation patterns for each lower body muscle will be described below.

1) **Gluteus Maximus (GM)**

   The traditional parallel squat was carried out in which the activity of GM was higher by 27.1% during the concentric phase of the squat cycle. However, during the eccentric phase, muscle activity decreases from 9.9% to 8.3% at load at peak load which is shown in Figure 4.3. This concludes that GM requires to be supported with more loads compared to other muscles and this can also be assessed with different forms of squats including deep, one leg squat, etc.

2) **Soleus (SOL)**

   One of the calf muscles SOL showed a greater variation and improved muscle activation during the ascent and descent phase between 5.5%- 5.6% as shown in Figure 4.5. The muscle activity declines between 31% to 60% phase. However, compared to other muscles, overall muscle activation is decreased during the full squat cycle for SOL.

3) **Hamstring (HAM)**

   It is confirmed that the hamstring was maximized greatly during the eccentric phase of squat from 4% when cross-compared with the other two phases. As knee flexion was reduced to 90 degrees during the concentric phase, the muscle activation was relatively reduced to 6.4% as described in Figure 4.2.

4) **Vastus Medialis (VM)**

   From Figure 4.1, we can understand that the VM muscles activate to the maximum of 70% at load at peak phase (31-60%) and are reduced to a greater extent at the ascent phase.

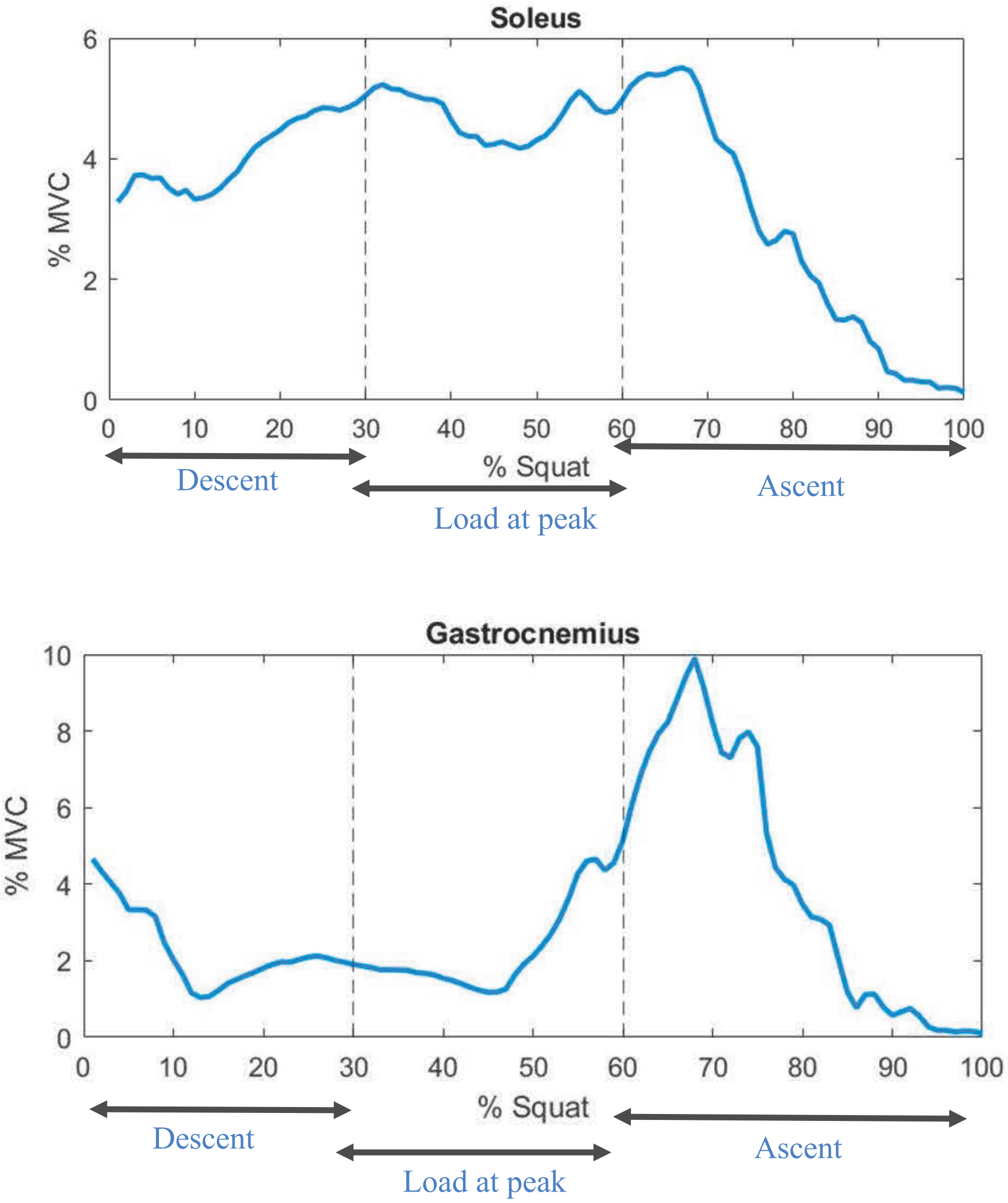


Figure 4.5 Maximum Averaged EMG activity of SOL and GA muscles for one squat cycle. Data were normalized to %MVC

5) **Rectus Femoris (RF)**

The quadricep muscles VM, RF and VL showed a similar activation pattern where RF muscles have maximum muscle activity of 116.2% during the descent phase (0-30%) while the other two have increased activation during load at peak phase (31-60%) % as shown in. Figure 4.2.

6) **Vastus Lateralis (VL)**

The muscle activation level is very low which is about 52.1% during load at peak phase (31-60%) when compared to VM muscles about 70% as shown in Figure 4.2.

7) **Gastrocnemius (GA)**

The medial head of the GA muscles, which are part of the squat control position, was less active throughout the start and final phases of the descent from (0-30%) as shown in Figure 4.5. The GA were more active with 9.88% during the ascending phase (61-100%) when compared to the load at peak phase (31-60%).

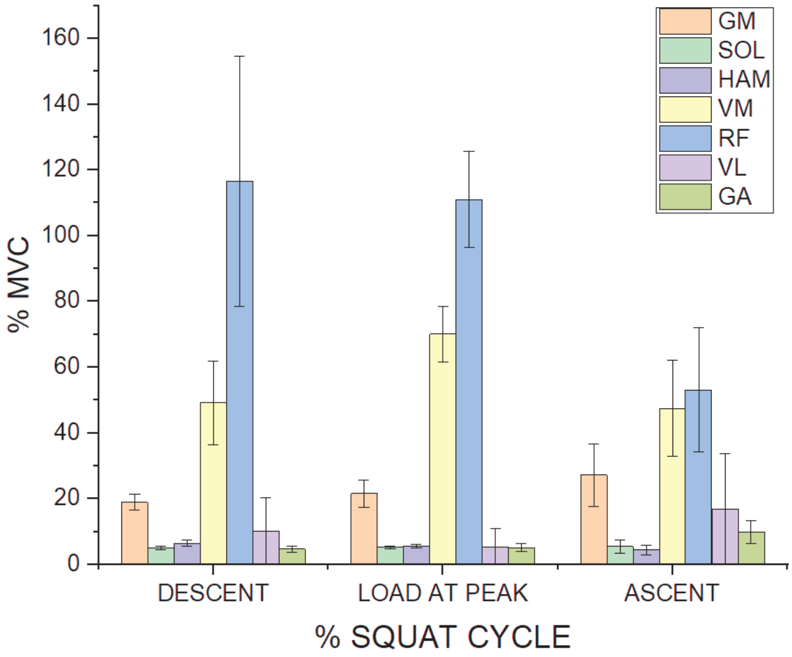


Figure 4.6 Comparative analysis of EMG activity of seven lower limb muscles. Data were normalized to %MVC

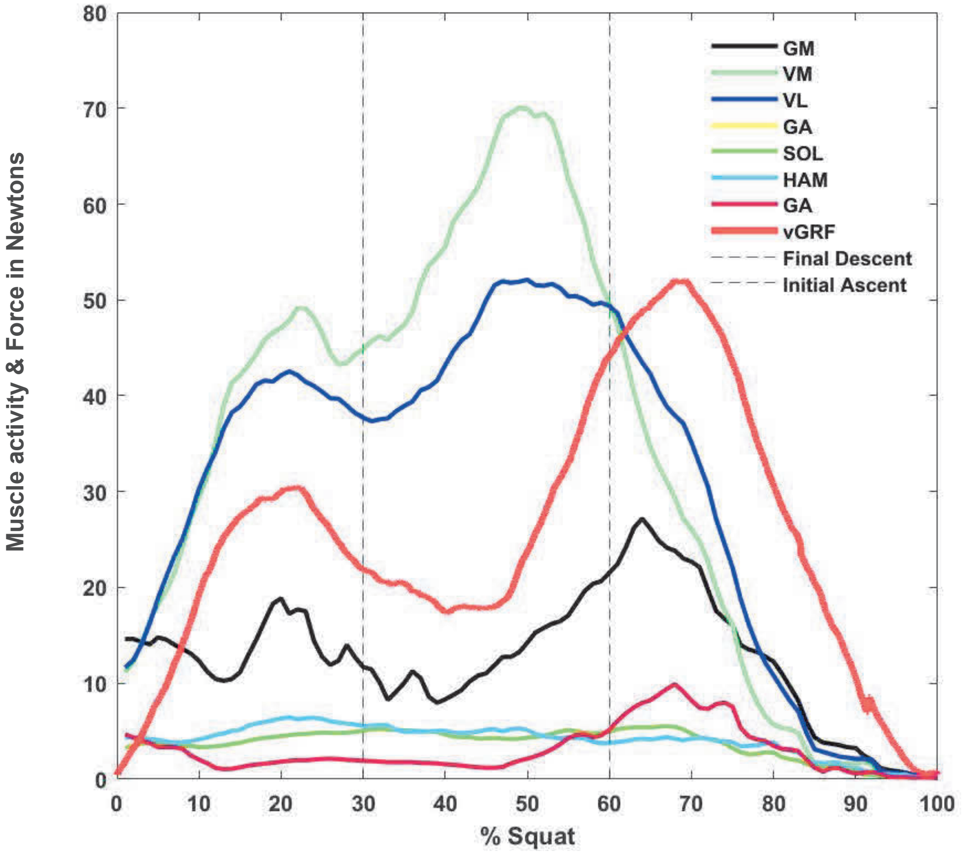


Figure 4.7 Correlation finding between the v-GRF and sEMG data of lower limb muscles

4.3 STUDY 2: SECOND EXERGAME TRAINING WITH MUSCLE FORCE VERIFICATION

In this study, we discuss the performance evaluation of the exergame using squat movements. The performance estimation quantifies the gaming session's muscle activity patterns compared to time-controlled deep squats. The EMG-based assessment is crucial in defining the control strategies and identifying the control points of PGMs in developing full lower limb suits to propose well-optimized dynamic difficulty adjustment (DDA) algorithms. The evaluation estimates the knee features and describes the significant difference in acquired parameters.

4.3.1 Improved Unity based exergame

A squat exercise game with varying loads dependent on the number of PGMs to actuate in accordance with the user's risk tolerance was implemented in the earlier study [45]. This restricts the load adjustment based on the degree of difficulty and amount of force applied throughout the session whenever assistance or resistance is required. Therefore, we developed this exergame design to overcome the above limitations and manage posture and depth to reduce injuries while performing deep squats. Moreover, the system limits the evaluation of the appropriate assist and resist muscle groups for the squat exergame exosuit development. This could help determine multiple muscle groups and develop exergame models tailored to specific subject groups to corresponding PGM exosuits.

We implemented two DDA conditions as described in Figure 4.8 based on the KS value obtained during gaming sessions.

DDA Condition 1: if the KS value is between 0.03 m/s - 0.04 m/s, the collectible moving object speed was reduced from 1.3 m/s −0.5 m/s, respectively.

DDA Condition 2: if the KS value is between 0.03 m/s - 0.04 m/s, the force applied for the PGM assistance increased from 60.17 N to 75.34 N for the HF pair and 25.01 N to 32.45 N for the KF pair.

In addition, the collectible moving object's speed was reduced from 1.3 m/s - 0.5 m/s, respectively. The above condition helps the user to control the gaming speed. As a result, the user adjusts the squat depth by performing parallel squats, to collect the moving objects. The risk of knee injuries was prevented in such cases. The previous work [46] and Figure 2.14 illustrate the difficulty levels, the corresponding range of movement speed and the force applied to the PGMs.

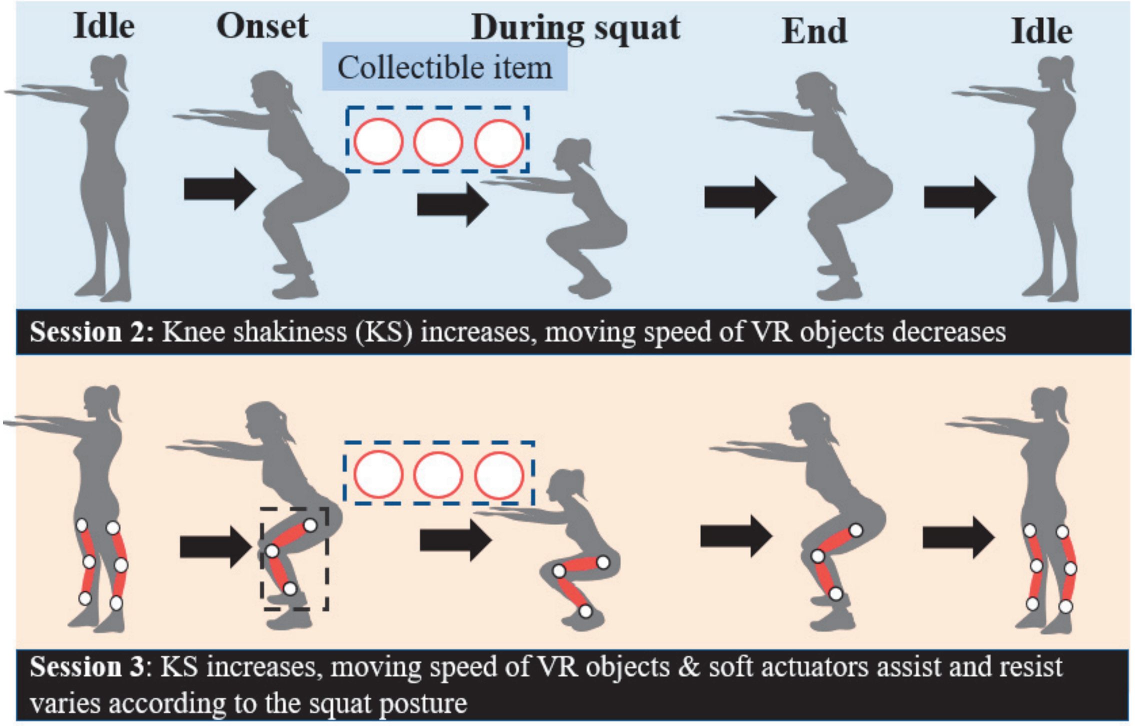


Figure 4.8 Phases of squats considered for exergame training distinguishing between VR only and VR and PGM sessions

4.3.2 Prototype evolution

Electromyographic (EMG) Configuration

Based on the previous study [46], it was confirmed that the users got motivated and showed improved performance with the motion data analysis. But to evaluate the system's performance and core muscle strength relationship, we assessed the muscle activity reduction with EMG pattern at five lower limb muscles. We employed the Delsys sEMG system (Delsys, Boston, MA) with the following specifications: Sampling rate: 1259 Hz; Bandpass filter: 30-500 Hz. The sensor locations tested in each subject were RF, VM, GA, VL, and BF, illustrated in Figure 2.13. The sensor locations were determined using the guidelines reported in the sEMG-based non-invasive assessment of muscles (SENIAM). Before the experiment, the anatomical locations were wiped with an isopropanol alcohol pad, and skin hair was shaved, if necessary [81]. The MVC was obtained by strongly contracting the test muscle to compare the muscle force levels. The task was repeated thrice for each tested muscle, with a 2-minute rest between each trial [82]. The MVC data acquisition for each muscle was executed according to the assessment tasks carried out [35]. The subsequent sessions 1, 2, and 3 as mentioned in Figure 4.9 were conducted on alternate weeks, and the EMG data were collected for each session.

The data acquisition includes joint angles from Vive trackers and the depth camera (RealSense D235i) and muscle activity from the EMG sensors. The control block was maintained separately and not backpacked to the user to avoid hindrance and discomfort during the training session. The control system, PGMs and exergame components were discussed in chapter 2 while the methodology with DDA mechanism was discussed in chapter 3 with detailed description.

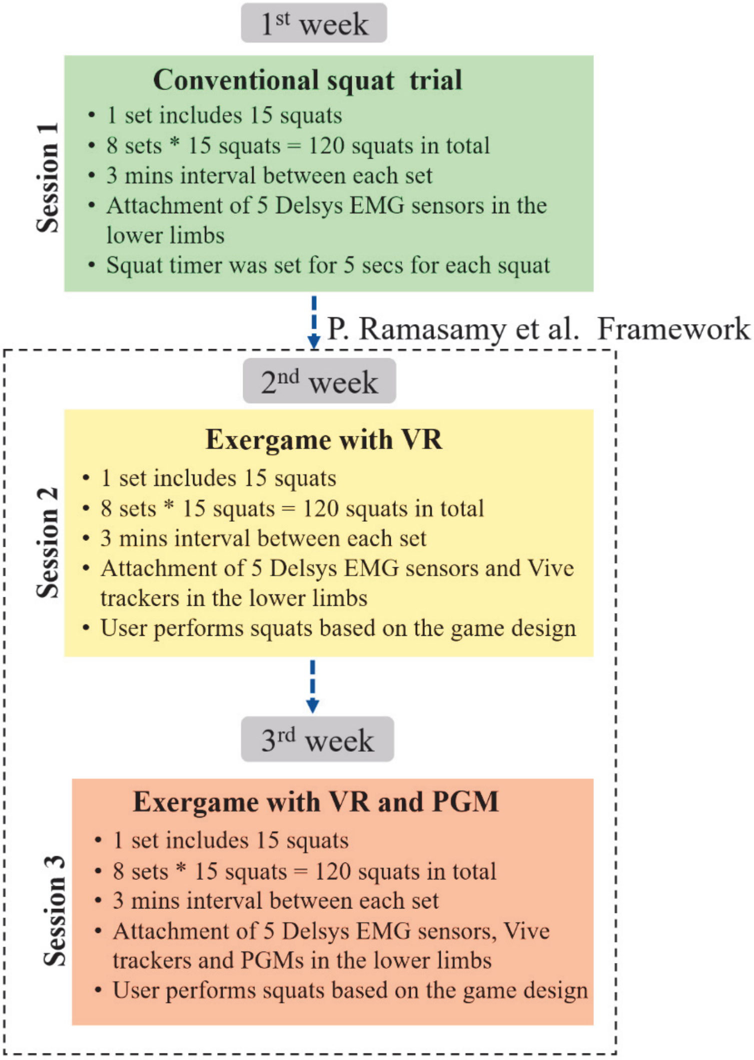


Figure 4.9 Methodological flow for differentiating exergame and conventional squat sessions.

4.3.3 Participants and user study

We performed the user study with seven healthy male subjects. The subject's age was 22.85 ± 1.21 years, weight was 57.85 ± 8.2 kg, and height was 171.71 ± 6.12 cm. The participants are university students without known neurological complexities or a history of treatments in their lower limbs. They are found eligible to engage in the study after a comprehensive assessment of their ability to accomplish five trial squats. The evaluation also includes concerns about their previous experiences involving exercise games and workout activities. After augmenting the game-play modules and soft actuators to perform the exergame training, the subjects confirmed no discomfort. All subjects were asked to sign the informed consent approved by the Institutional Review Board (C-342) under the ethical guidelines in the Declaration of Helsinki (Hiroshima University). Figure 4.9 illustrates the user study flow, differentiating the sessions and related equipment employed during the training.

Session 1 (Conventional squat): The user was instructed to perform a time-indicated conventional squat for 5 seconds based on the timer set with the app to ensure proper squat timing. During this session, the user performs only the traditional squat, which acts as a control group without introducing the VR space with exergame training.

Session 2 (Squat + VR): The novel technique proposed in the present study employs collectible game objects on the user's ski course. The collectible items were designed to be easily attainable by the user if a half squat was done appropriately. After calibrating the initial position through the HMD, the height of the collectible objects was adjusted according to the user's dimensions, coded with the UNITY algorithm. This session utilizes DDA condition 1 during the experimental training.

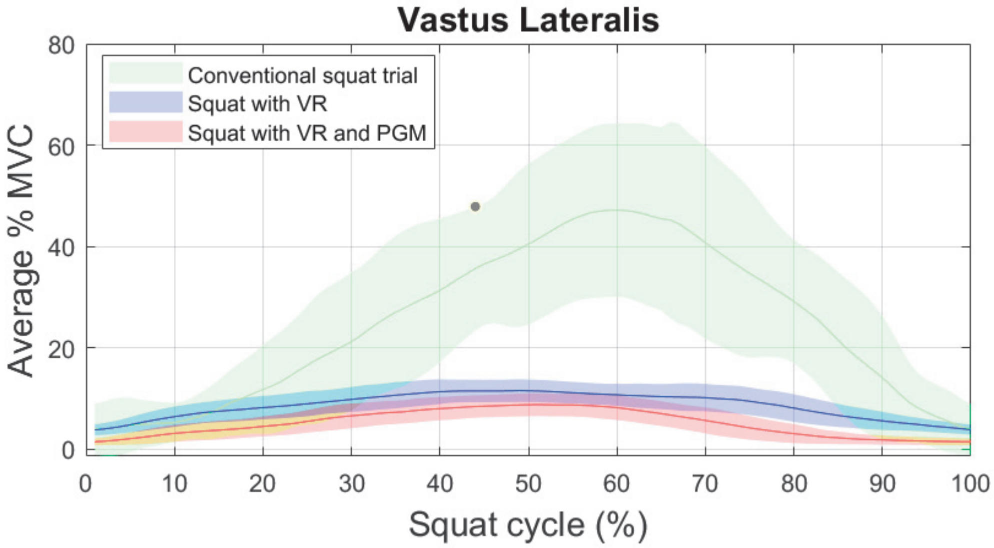
Session 3 (Squat + VR + PGM): This session combines session 2 and the PGM exosuit. This session utilizes DDA condition 2 during the experimental training. The participants were briefed on the sessions and gaming parameters before the experiment. The user gets familiar with the gaming conditions and difficulty level during session 2. The EMG sensors were attached to the predefined locations during this session.

4.3.4 Results

We obtained the knee features for all the sessions and presented them to evaluate the motion data variation and their effects on the performance of knee functioning during squat-based exergame training. For session 1, the joint angles obtained from the real sense depth camera were used to calculate the knee features such as knee shakiness, knee distance (KD) and squat depth (SD). The acquired data were normalized, smoothed and cleaned through the advanced machine learning toolbox of MATLAB 9.12.0 (R2022a). For sessions 2 and 3, UNITY-based in-house built-in algorithms were used to calculate the knee features. The acquired parameters were then compared using Analysis of Variance (ANOVA). The increased shakiness in the knees ensures the weak functioning of the lower extremity and causes mobility problems in a very short time. It is mandatory to have continuous monitoring of knee functions. Figure 4.14 illustrates a more significant reduction of the KS parameter based on the p-value ($p < 0.01$) comparing the conventional squat with squat + VR and squat + VR + PGM sessions.

The estimation shows the interpretation of the controlled pattern of squatting under exergaming conditions. The controlled pattern reduces knee muscle damage, whereas traditional squats lack KS management. It was also observed that the KD and SD also reveal a significant reduction based on the p-value ($p < 0.05$) comparing the conventional squat with squat + VR and p-value ($p < 0.01$) comparing the traditional squat with squat + VR + PGM. The results of KD confirm that subject-oriented eased training transforms into game-oriented focused training without external environment distractions in exergaming sessions. From the results of SD, we found that it is impossible to distinguish the posture (parallel or deep) while doing traditional squats. But in sessions 2 and 3, with the calibration, the collectible objects will appear in such a way that users align themselves to do controlled parallel squats lowering the depth.

The recorded EMG data were rectified and normalized using the MVC to obtain the %MVC. Each trial was normalized to a squat percentage (0% to 100%) using MATLAB to compare the squat phase and sessions [83]. The averaged muscle activity between the three sessions for both assist and resist groups is depicted in Figure 25 and 26. The resist group shows a high muscle activity reduction compared to the assist group. The EMG data were analysed using the paired t-test to determine the significant differences between the sessions.



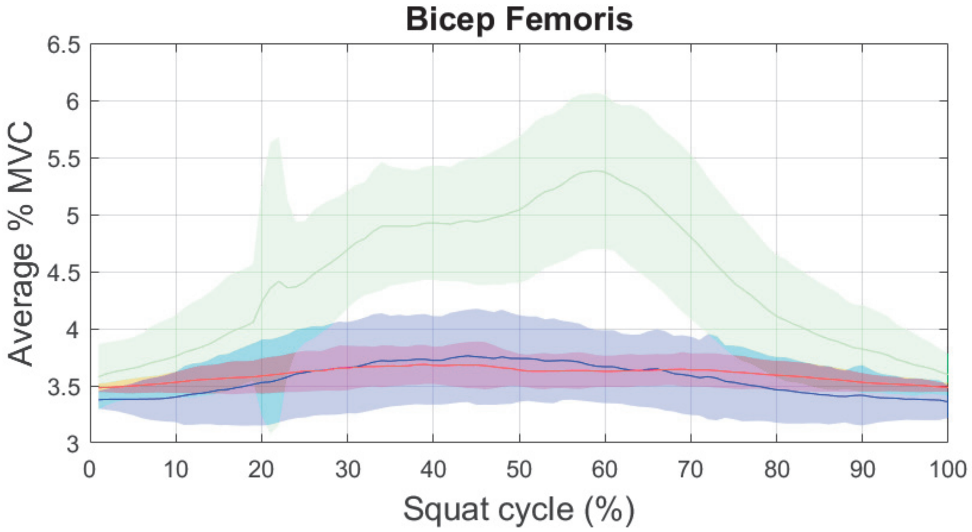


Figure 4.10 Normalized EMG pattern of resist group muscles (VL and BF) averaged for one squat cycle

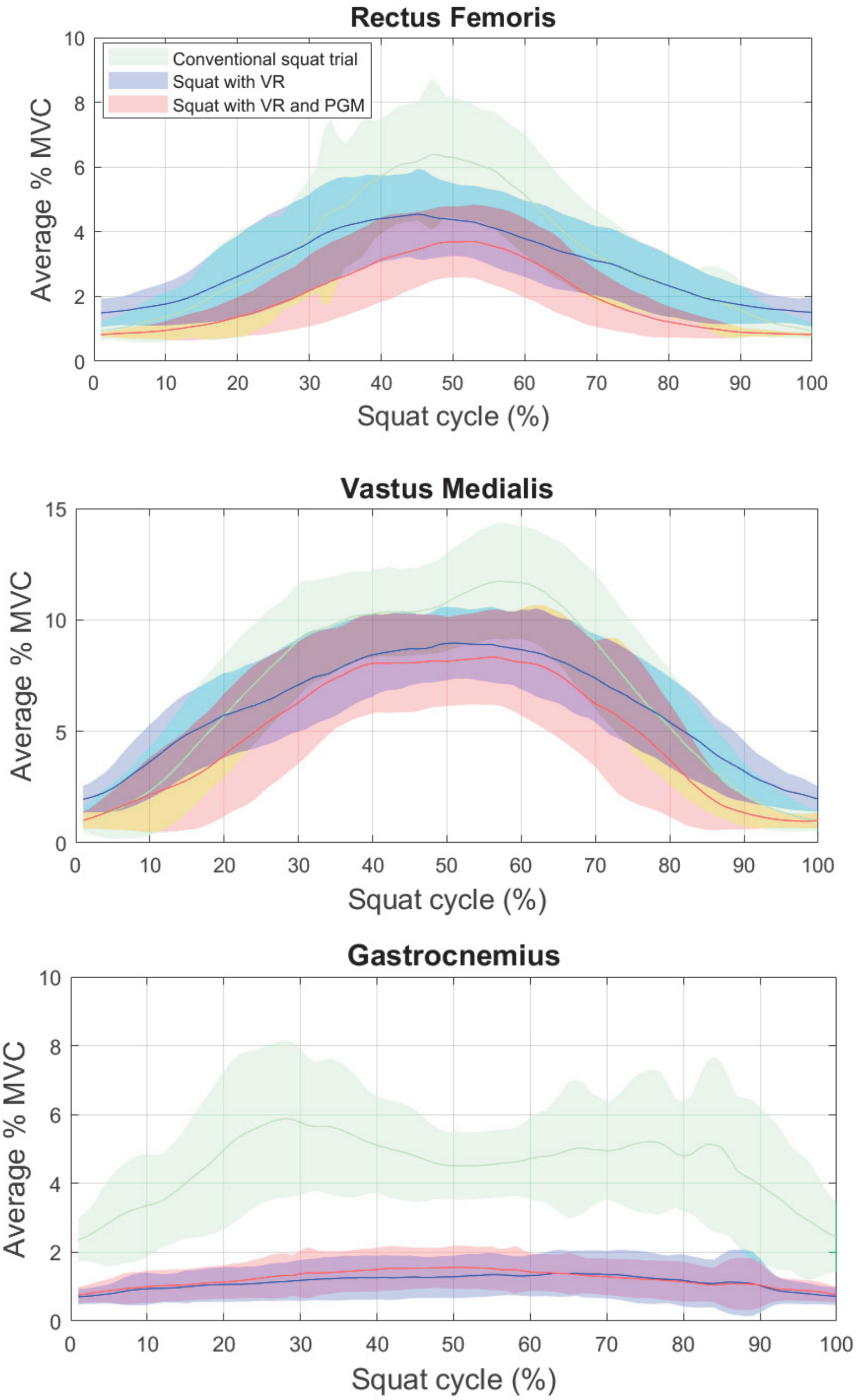


Figure 4.11 Normalized EMG pattern of assist group muscles (RF, VM and GA) averaged for one squat cycle

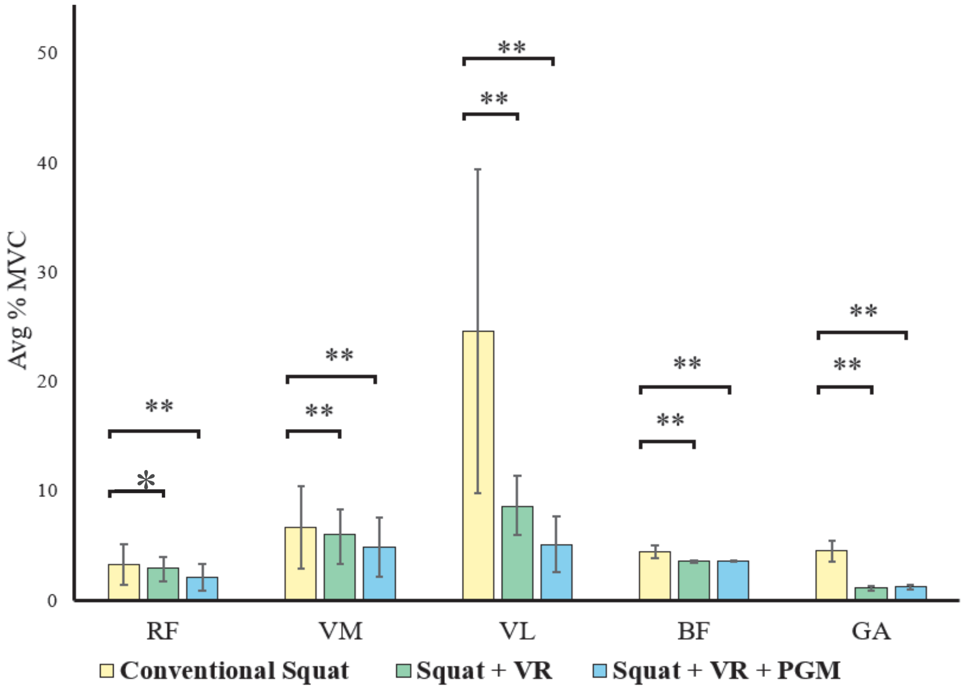


Figure 4.12 %MVC difference for assist and resist group lower limb muscles during conventional and exergame squats

4.3.5 Discussion

We normalized the data using the logarithmic transformation to perform the paired t-test using the subject's average data. However, our normality check was negated in this case; a nonparametric method called the Wilcoxon Ranked test was used to check for significant differences. The average %MVC for all muscles measured is presented in Figure 4.12. During the squat motion, the assist group (RF, VM, GA) and resist group (VL, BF) showed decreased muscle activity in session 3 compared to session 1. This confirms that PGM actuation helps reduce muscle activity compared to traditional squats. However, in this case, the resist group was provided with a fixed force of 90.51 N throughout the sessions. The assist group's muscle activity variation was lower than that of the resist group. This is because the force range varies according to the subject's squat type. Also, a significant difference exists between sessions 1 and 2 for VM, VL, BF, and GA. This confirms that the exergame gaming conditions maintain the squat type based on DDA parameters.

In this letter, we discussed the design and development of an exergame module to overcome the limitation of the previous study [45] of varying the PGM counts based on the risk strategy during the training. We have included the different exergame sessions based on dynamic difficulty. While performing the exergaming training simultaneously, we assessed the users' knee features and muscle activity in all sessions. The work consists of a comparison of traditional-based crouching with gaming exercises. This comparison would help to understand the importance of exercise-based games through increased adherence to home exercises. The role of the muscles connecting with the knee joints (RF, VM, and VL) must be to help in consistent contraction, which in turn stabilizes the dynamic postures. Based on the statistical results obtained from the knee features and muscle activity, in-phase consistency of the muscle fiber contraction is achieved through the DDA technique. Although the transition of the fatigue phases causes the user to react slower, the PGM attachments help to react faster, maintaining immersion and attention towards the game.

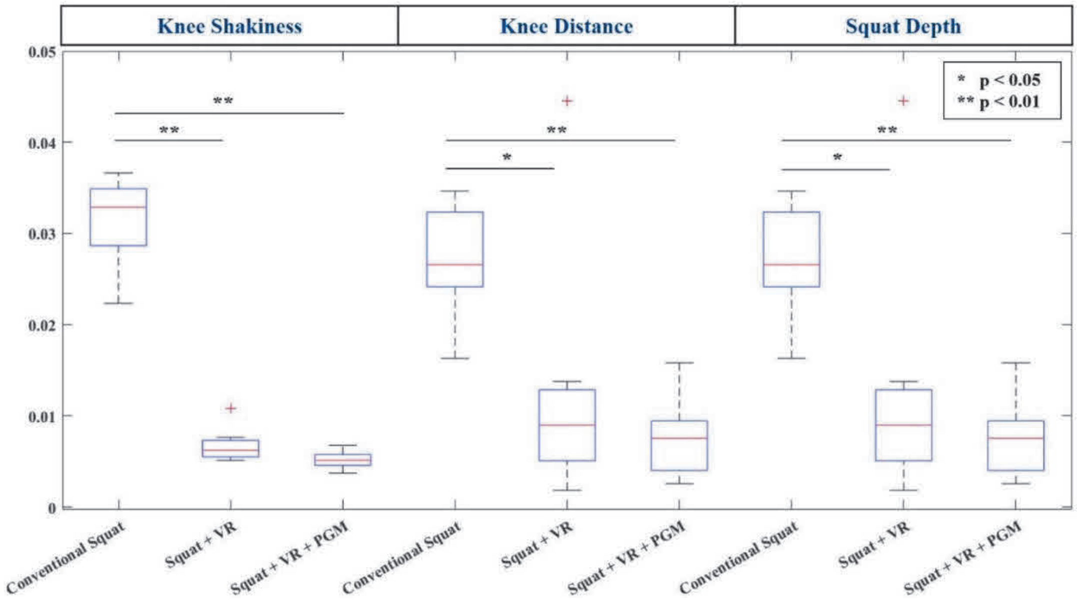


Figure 4.13 Analysis of motion data during conventional and exergame squats (knee features) obtained from depth camera and Vive knee trackers

Moreover, we can also confirm the enhancement in cognitive function and motor skills with personalized patterns of squat training. We demonstrated the possibility of muscle unloading effects by introducing varying difficulty levels while comparing the conventional and exergaming sessions. Although several previous studies on EMG muscle activity reduction have been implemented, our study quantifies assist and resist muscle groups and actuates them based on force values. Our evaluation produces better results by incorporating several enhancements such as quantified force level input, assist and resist muscle group actuation, location specific PGM length, improvement in the actuation delay, and squat phase detection. Muscle activity reduction results are higher compared to walking studies [42].

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4.4 CONCLUSION

We performed the exergame training as a pilot trial of one month with healthy subjects where we considered assessing the motion data and physiological characteristics of the users involved in the study [46]. There were explicitly higher significant differences in motion data between sessions 2 (DDA) and 3 (DDA and PGM). While taking skin temperature into consideration, negative changes are found during all sessions. Since the pilot study already assessed with motion data, we have planned to evaluate the muscle activity pattern for analyzing the performance effect whether the muscle gets loaded or unloaded with squat motions.

This assessment was done through sEMG measurement. The DOFs are limited to hip extension and flexion and knee flexion as it involves attachment of maximum sensors and actuators. The obtained data showed better improvements and maximum muscle unloading compared to the conventional squat sessions. From the study of proposing control strategies, we found it is possible to control the actuators using minimal sensors and GRF can also be used to provide control optimization. Therefore, through the above studies, we attempted to address it is also recommended to focus on various DOFs of lower limbs and implement the control optimization to reduce discomfort during squat exergame training.

Chapter 5: Conclusions and future work

This research on the integration of soft actuators-based force feedback with exercise-based gaming sessions emphasizes to realization of the isolation free environment and evidence-based adaptation for promoting ADL through physical exercises. This also adds to the enhancement of interest and motivation through the implementation of the DDA algorithm with force feedback applications. The demand for rehabilitation and dependence on therapies will be constantly increasing and it is always recommended to have an efficient application to improve both physical and mental health without compromising on the limitations such as adaptation, augmentation and interaction.

We are successful in implementing the integration to support the effective maintenance of posture with the assessment of the knee features and muscle activation patterns. The application can serve as an efficient system for implementing telerehabilitation training enabling the target group and clinical centres to get easy access to the current conditions and improvements on their motivation to follow the training methods. The requirement of control strategies is demanding since many studies lack optimal control techniques limiting the subjects' performance. The control methods of using EMG and GRF as optimizing parameters could help us develop an efficient dynamic control for soft actuator inflation. We have observed reduced muscle activities of the lower limbs due to the control of squat posture with the DDA method involved. This application could be a better option for power or strength training of sportsman and fitness persons.

The advantage of the developed system includes the self-customized design, efficient control for augmentation of a force feedback system, and home-based and secured training with realistic feedback and self-estimation on the risk levels. However, there are several prospects for improvement and limitations on problem-solving were required to have an efficient product to contribute to the distinct target groups in the world.

The system was mainly based on the hip and knee flexion-extension motion while utilizing the actuators for dynamic assistance and constant resistance. This configures the suitable type of DOFs for squat motion and effective selection was done for DOFs. The ankle DOFs were not considered as the knee and hip are significant body parts for supporting the squatting motion.

The participants reported the PGM placements were comfortable and actuated effectively during the squat trial. In addition, by achieving the highest possible score, the exergame helps keep participants engaged in the activity. The knee indicators also showed a significant reduction and better progress in squat posture maintenance and the chances of a decrease in ACL injuries. The proposed risk level estimation technique with the VR-based gaming platform would eventually contribute to an interactive system with the value-added role of integrating soft actuators for rehabilitation and therapeutic exercises. There are limitations and future prospects to be described in the next chapter.

There is a considerable chance of improvement for the current exergaming system. To increase the immersion level, adding more in-game parameters was planned to increase the challenge level and identify them according to the user's risk level. We consider improving the compatibility by utilizing more advanced features of depth cameras for motion tracking, eliminating the use of trackers, which leads to minimalization of sensors. It is also recommended to deploy the techniques for varying squat phase thresholds, which will help to enhance and evaluate the user's performance efficiently. We also plan to consider a machine-learning approach for knee tremor prediction and observe its accuracy with additional kinematic features.

Although the soft exosuit can actuate based on user activity, the wear-and-tear nature of the PGM for long-term usage is still questionable. The future scope will be improved by employing individual PWM valves for assist and resist blocks to realize the higher intensity of force levels, further reducing the delay time for inflating the PGMs and conducting a feasibility study using elderly subjects. Force sensor-based quantification methods will be adapted to improve the user's comfort level.

We have used a depth camera to acquire the motion data, mainly to detect the knee indicators. Still, we plan to assess more parameters using the motion capture sensors. The future direction includes applying the defined control points while integrating soft actuators, examining the usability and performance effects, and analyzing the prototype wearability. Considering the prototype's bulkiness, we have planned to minimize the number of sensors by choosing the appropriate muscles to perform squat motion based on the estimation done with this research.

The study's limitation and the future scope include exploring the frequency component of the s-EMG while implementing a better correlation study with the GRF pattern, as the current work only involves amplitude analysis. Also, incorporating machine learning algorithms is essential to fine-tune and optimize the gel muscle actuation based on user needs. It can be useful to use the purposes from Chapter 1 as an organizing structure for this chapter. The chapter should also include a discussion of any limitations of the research and should end with your final recommendations – practical suggestions for implementing the findings/outcomes or additional research.

The limitation also exists with the cognitive evaluation in which we plan to implement the user studies with an electroencephalography (EEG) system to examine their level of immersion before and after the intervention. We also highlight the difficulty in exploring more posture balance studies, especially with squat motions, given the limited number of trials, including limiting the subgroup analysis. The studies will be examined in the future by comparing the other squat posture-based exergame designs available.

It is also necessary to focus on the additional DOFs of the ankle joints as they were not included in the past studies. Identifying the functional dependence of the ankle movements depending on the squat posture will be helpful, which effectively implies the importance of posture control. The center of gravity (COG) and center of pressure (COP) parameters will be considered to analyze the foot pressure parameters for different individuals during squats when the posture changes. From this, we can identify the relationship between the plantar pressure and posture method considered when the squat depth changes because of structural deformations. This also directs us to involve various insoles to ensure the plantar pressure distributions depending on the squat motion.

Chapter 6: Expert interview (Taoyaka Program Onsite Team Project)

There are several challenges exists to commercialize the human augmentation-based devices used to enhance the human ability. These challenges include both in medical and entertainment fields. In our study, we have developed the system that is useful in enhancing the physical health with the exercise enhanced parameters while the virtual reality concept was introduced to motivate the users by providing self-entertainment and immersion outputs in ensuring mental health improvements. On the other hand, it is also mandatory to evaluate the perceptions for resolving the social and cultural-based issues in commercializing the augmentation systems in the real world. To outline some of the challenges, I have conducted an informal interview with an expert, Mr. Ariaki Higashi who have 20 years of experience as a project manager in medical device manufacturing which is shown in Figure 7.1.

His works includes the development of rehabilitation equipment approaching the aspect of kinematic measurement to effectively improve a person's motor skills. He had several collaborations with clinical doctors who have been measuring athletic performance using evaluation methods that have remained unchanged for decades and understood the importance and requirement of exercise evaluation system that incorporates digital technology. There were only few devices that combines medical care and IT to focus on rehabilitation providing a wide opportunity for advanced performance analysis of human ability. The major focus of his work is to introduce a quantitative evaluation through measuring instruments into the field of rehabilitation, where qualitative evaluation is predominant.

Importance of quantitative evaluation for human motions

The quantitative assessment is very crucial for assessing the qualitative features of segmentation, recognition and performance variation for processing the effects before and after treatment with any devices. It is very complex to verify the effects before and after treatment in rehabilitation unlike drugs. Hence the development of kinetic measurement devices could facilitate in explaining the treatment results to the patients and common people to understand the symptoms. The current research includes the utilization of the developed equipment to provide information on the improvement of performance when rehabilitation is continued. There is higher demand for the measurement of gait in several medical institutions. Most rehabilitation centers treat patients with unilateral paralysis, which primarily affects walking. It is believed that the patient's gait can be efficiently improved if the patient's condition is evaluated by collecting their data and processed for providing specific feedback on the affected region of the body as shown in Figure 7.2.

This will help to focus on the region of impairment with effective evaluation rather than assessing on the whole body. Motion analysis in healthcare has become a societal necessity, and in the future, upper limb analysis will also be needed to improve QOL, such as better feeding movements. He has given reference of Dr. Kimura of Seiwakai, who wants to focus on the movement of fine joints, particularly the fingers. As a result, there is a great demand for measurement equipment for large joints, as there are currently few available. In any event, feedback indicates that a technology that uses a camera to measure whole-body motion without the need for markers is required.

Figure 6.1 The interview session outlined the significant requirement of IT combined digital technology for rehabilitation

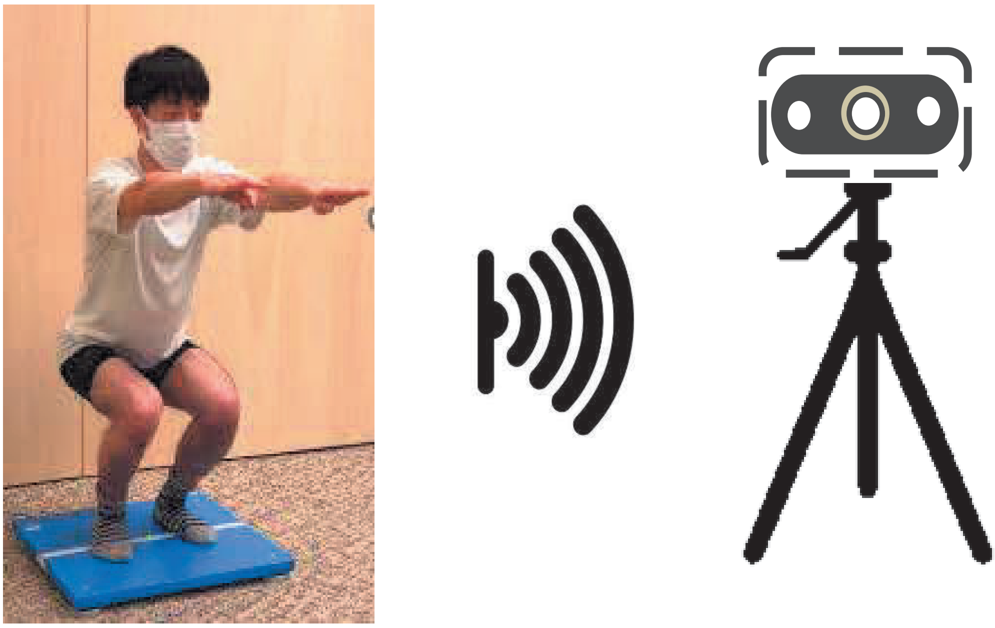

Figure 6.2 Major objective to develop advanced marker less motion capture systems for quantitative assessment of human motions

The interview is mainly focussed to include the perceptions on the social and cultural aspects of using IT combined rehabilitation-based technologies in the following criteria of

1. Clinical mental health
2. Mental wellbeing
3. Physiotherapy and rehabilitation
4. Workforce education and clinical skills

Also, we would like to know more about the issues or challenges in development and design of medical devices and related interfaces in the following aspects of

1. Technical concerns
2. Social benefits
3. Economic benefits
4. Data privacy and obligations
5. Media and advertisement

The development approach depends on the needs and challenges of conducting research, surveys, interviews and collaborating with clinicians to comprehend the gaps in current mental health management. It also depends on the brainstorming and conceptualization of technologies that address the identified needs. When addressing the potential socioeconomic and geographical barriers that limit access to the use of the developed technologies, it is mandatory to find the sales channels to introduce equipment to relieve the labor shortages. From the interview, we understood that it is very complex when considering the installation of the equipment in the nursing homes since they do not have funds. They require financial benefits to reduce the workforce and over these barriers for their health security. When considering the financial barriers for the development, adoption into insurance system is highly recommended. This adoption could help them with the option of standardizing judging on the effectiveness of rehabilitation done. The therapists always find it challenging to provide fair evaluation because of the qualitative analysis. He is very interested in implementing a system providing quantitative feedback that would also be accountable for creating a great impact on the social economy.

Certified qualifications approved by the prefectural government are necessary for sales management, incurring substantial costs. This includes registration fees for national and prefectural approval, along with post-sale management expenses. The classification system involves Class 1 devices, harmless to the general public, receiving registration upon application approval. Class 2 and higher categories demand considerable funds and a minimum of two years for approvals, involving multiple examinations and tests. Pricing determination relies on registration fees and vendor brokerage fees, which facilitate communication with hospitals, consequently raising prices in response to market demands. Profit margins are set high due to limited sales partners available for medical devices. Feedback collection primarily occurs directly from hospitals, as they are the direct customers. In specific cases, feedback is gathered from patients when collaborating with universities. Developing medical devices for mental health management requires a holistic approach that prioritizes efficacy, safety, user experience, and adherence to regulatory standards while addressing the specific needs of mental health patients and professionals.

When it comes to data privacy and responsibilities, heightened measures are in place. Simultaneously, there's a focus on forging partnerships with new networks to create secure software aimed at addressing privacy concerns. For existing devices equipped with camera-based detection, an automatic facial blur function engages during patient assessments to ensure privacy. Adherence to safety standards remains paramount through the implementation of the Quality Management System (QMS), for which maintaining accurate quality records falls under his view. Incorporating AI algorithms and introducing VR systems necessitates obtaining written consent from patients for any secondary use of their data. Additionally, it's a business practice to offer compensation in exchange for data.

Conclusions

This session has provided insight into the iterative nature of designing and developing medical devices, considering not only technical aspects but also the social and cultural implications among the general population. During our discussions, we delved into the concerns that elderly individuals believe regarding digital technologies, set against with their enduring reliance on traditional rehabilitation methods. Moreover, we explored their attitudes toward using VR and AR devices, understanding how these technologies can influence both the satisfaction of patient needs and the efficacy of therapists' practices. It is evident that there's a long-term need for the development of advanced quantitative assessment technologies. These innovations aim to demonstrate to the general population the importance and effectiveness of analysis on their physical and mental health when compared to traditional practices. Hence, Our future work lies in the development of advanced motion capture systems. The aim is to integrate a comprehensive range of features that enable the performance of both quantitative and qualitative assessments. This integration seeks to offer a holistic evaluation approach for enhanced analysis and understanding.

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