論　文　の　要　旨

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)

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Strengthening muscle activity and promoting health with proper physical exercise must be the vital phenomenon for all individuals which helps in managing the lifestyle without malfunctions, especially with muscular conditions. The effective functioning of the lower limbs is essential as it involves mobility, a primary factor in maintaining an active and independent lifestyle. Dependence on hospitals and rehab therapies is showing a rapid increase with the increasing elderly population in Japan. The aging society also experiences loneliness and social isolation leading to psychological stress and depression, etc. The lack of self-motivation in younger adults and middle age groups leads to ignorance of physical activities of daily life (PADL).

To address both physical and cognitive health issues in a single system, we attempted to design an exercise-based game integrating soft robotic suits for introducing dynamic difficulty adjustment (DDA) in a virtual reality environment. The DDA technique involves the optimization of the three P parameters of posture, pace and progression. This is done through the adjustment of air pressure applied to the soft pneumatic actuators and movement speed variation through the program coded with Unity. We developed the exergame based on the squat motion adjusting or maintaining the posture from the deep squat to the parallel squat reducing the injuries on overstretching of the lower limb muscles. Primarily, the exergame training with squat motion was evaluated to verify the performance by acquiring the knee parameters (knee shakiness, knee distance and squat depth) and the physiological features (heart rate, skin temperature and galvanic skin response (GSR)).

From this study, it was proved that the DDA algorithm significantly influences the performance of the lower limbs to acquire proper squat posture. Also, an extensive study was conducted to evaluate the muscle unloading during both assistance for knee flexion and hip flexion and fixed resistance for hip extension provided by soft pneumatic actuators. In the second study it was observed that both resist group muscles and assist group muscles showed better muscle unloading during the soft actuators-based sessions. The following attributes were focused during the development of exergames, and the lower limb soft actuators suit which contribute to the enhancement of the overall health and wellbeing.

Exergames:

- Simple and interesting game design for emphasizing human-computer interaction.
- Easy integration of soft actuators to enable the difficulty variations.
- Notified of scores and squat counts for a better understanding of the performance.
- Audio and visual feedback to intensify the task accomplishment.

Soft actuator based-lower limb suit:

- To enable portability and flexible attachment, use of low pressure diffused muscles with small canisters.
- Cost effective in terms of manufacturing and maintenance.
- Corresponds to three different degrees of freedom (DOFs) for joints of the lower limbs.

The structure of the thesis is as follows:

In Chapter 1, we discuss the detailed study of background on exergames and human augmentation utilizing soft robotics. The background section is followed by a discussion on the motivational aspects that are directed to initiate this research. Then, we discuss the previous studies associated with this research classified into exergame-based training and soft exoskeletons for the lower extremity. The second classification is broadly divided into two ranges of applications in rehabilitation for enhancing physical health and mental motivations for enhancing cognitive health.

In Chapter 2, we discuss the biomechanics of the lower limb related to the squat cycle and novelty in the range of different specifications. Next, we will give a concrete explanation of the prototype evolution and various interfaces involved in designing the exergame module, sessions and control block. The exergame components and soft actuators widely called pneumatic gel muscles (PGMs) are discussed with the air-pressure relationships to understand the working principle of the low-pressure-based actuation.

In Chapter 3, we will discuss the PGM force measurement experiments involving the air pressure-force relationships producing effective force feedback system and explanation on introducing the DDA concept to define the difficulty level. This DDA implementation influences the evaluation parameters selected for analyzing the performance effect.

In Chapter 4, we discuss the different user studies conducted under this research. The user studies were detailed with their corresponding methods, features for analysis, results and discussion. The first user study is the field of rehabilitation pilot study with healthy subjects to find the variation in their performances. The second study proposes a control strategy through soft wearable devices setting the EMG and GRF as the control influencing factors. With the third study, sEMG estimation was done to identify the muscle unloading aspects during exergame training through the engagement of healthy subjects.

In Chapter 5, we make conclusive statements on our research studies completed and summarize the outcomes. We also discuss the prospects of our work and several viewpoints on the exergame training programs to review the impacts.

In Chapter 6, I discuss the expert's perceptions on the social and cultural challenges of design and development field. This includes the design and development of augmented and virtual reality-oriented rehabilitation technologies primarily motion capture systems.

4. 主論文と引用既発表論文の対応

主論文	既発表論文番号
Chapter 1: Introduction and background	Ⅰ－1, 2 Ⅱ－1, 3
Chapter 2: System description	Ⅰ－1, 2
Chapter 3: Methodology	Ⅰ－1, 3
Chapter 4: System evaluation	Ⅰ－1 Ⅱ－1, 3
Chapter 5: Conclusions and future work	Ⅰ－1, 2 Ⅱ－1, 2, 3
Chapter 6: Expert interview (Taoyaka Program Onsite Team Project)	