A Personalised Monitoring and Recommendation Framework for Kinetic Dysfunctions: The Trendelenburg Gait

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ABSTRACT

Kinetics and kinematics have been the focus of a lot of research throughout the years, and technological advances have contributed towards advanced monitoring and analysing of motion. Focusing on Trendelenburg Gait, an abnormal gait, a personalisation framework for monitoring and evaluating the movement is proposed in this paper based on a number of factors, such as individuals' body composition, motion mechanisms, capturing process, analysis tools and information presentation techniques. A formal description of such factors allow for a better understanding and deeper analysis of the critical points, enabling the framework to provide improvement recommendations, applied in interdisciplinary contexts such as rehabilitation, medical applications, strength and conditioning, and sport performance.

CCS Concepts

•**Hardware** → *Sensor devices and platforms;* •**Social and professional topics** → *Medical technologies;*

Keywords

Trendelenburg gait; kinetic dysfunction; personalisation and recommendation framework; ultrasonic sensors

1. INTRODUCTION

The general aim of clinical movement analysis is to identify and understand mechanopathology and pathomechanics. With the application of biomechanical analysis, injury causality could be identified and the kinematics associated with an injury can effectively be treated, leading to improvements in quality of life and performance. From a rehabilitative perspective, it is possible to identify the risk of re-injury on an individual basis through the application of biomechanical kinematics and kinetics. The identification of causality often requires precise analysis, as patients frequently present a plethora of compensatory movement patterns. Such compensatory deficits and impairments are often more noticeable than the underlying cause [15], making the diagnosis process even more challenging. However, quantifying the mobility state of a medical disorder and determining the neuromuscular-skeletal contributions to that state helps in prescribing treatment and assessing the outcome with greater confidence. The most accurate systems for capturing gait patterns are camera-based, which require an expensive experimental setup and a complicated calibration phase [1, 15]. Such systems calculate and report reduced internal hip abduction moments and external knee adduction moments following intramuscular hypertonic saline injections [10]. However, research regarding gait analysis on the Trendelenburg gait pattern is limited. Examination of this gait pattern arises from the Trendelenburg test, in which the individual is seen *"standing on the treated (affected) leg and raising the buttock of the other side up to or above the horizontal line"* [27]. Failure of the test implies being unable to stand on this position [27].

Advances in computer technology, simulation models, and artificial intelligence have increased the potential of designing and developing personalisation, both on-demand and in-time, mechanisms. Utilising computational techniques to model patients' locomotion offers a personalised experience, improving individuals' life quality. However, the design of such effective and efficient personalised platforms is an elusive task, as it is related to an interdisciplinary background, such as biomechanics and computer engineering, taking into account various physical, human, technological, and application design factors. The interrelation and interdependences among the aforementioned factors are defined by the characteristics of the designed application, such as anthropometric data, human locomotion kinetics and kinematics, data transmission mechanisms, and tools of data visualisation. In this context, this paper contributes to the design for personalised experience by proposing a factor-based framework that can be used to monitor, evaluate, and recommend improvements on the treatment process of Trendelenburg gait.

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2. RELATED WORK

Trendelenburg Gait has not received a lot of interdisciplinary attention. To the authors' knowledge, only two teams [1, 10] have formerly researched this abnormal gait pattern either implicitly or explicitly. Existing monitoring systems [12, 18] are not specified for Trendelenburg gait analysis, but they could be applied in this domain. However, these systems model the human body based on the average human metrics, thus disregarding the characteristics of each particular person. Nonetheless, personalisation, recommendation and adaptation have received a lot of research in other contexts than kinetic dysfunction domain, with promising results in terms of enhanced user experiences and enriched provided services [8, 24]. Given that, in the context of medical applications and kinetic dysfunction, patients' locomotion and kinetics have a great impact on the treatment process, a personalised monitoring and recommending system could add value to the existing capturing systems and boost the supported procedures. This requires in depth understanding of the patients' locomotion and kinetics combined with exploitation of existing wireless wearable tracking systems and high-level system adaptation.

3. TRENDELENBURG GAIT

The Trendelenburg gait pattern, named after German surgeon Dr Friedrich Tredelenburg, is an abnormal gait caused by weakness of the abductor muscles of the lower limb, gluteus medius and gluteus minimus [25]. When a person walks with such an abnormal gait, the hip joint is subjected to stresses in areas not normally stressed during gait. This results in the development of other pathologies of the bones and cartilage in the hip and knee, such as arthritis or premature wear in the cartilage hip joints [26, 28]. Trendelenburg gait is also associated with the development of pathology at the knee or ankles over a period of years [25], e.g. valgus of the knee is caused by the laterally displaced weight over the hip [15]. It is characterized by a trunk shift over the affected hip, due to weakness of the hip abductors, and is best visualized from behind or in front of the patient. Observation of the patients' gait from the side enables the examiner to detect stride and step length deficiencies; motion of the trunk and lower extremity in the sagittal plane, including the extensor or gluteus maximus lurch, in which the patient extends the trunk posteriorly to compensate for weak hip extensors. It also enables detection of ankle dorsiflexor weakness and foot drop, leading to the inability of the foot to clear the ground, which is compensated for by excessive lower extremity flexion to facilitate foot clearance of the ground. The integrity of the hip abductor muscle function is determined by clinical and X-ray assessments and by the Trendelenburg test. While no treatment modalities currently exist, medical management attempt to deal with underlying causes, e.g. pelvic support osteotomies lead to a significant improvement in posture, gait and walking tolerance in patients who have untreated congenital dislocations [6, 7]. Research has shown the importance of strengthening hip abductors, quadriceps and hamstrings, resulting in reducing the degree of Trendelenburg gait [16]. The purpose of the treatment is to increase the otherwise abnormal range of motion in the hip and trunk. Visual feedback collected from the patients' gait is used for adjusting the physiotherapeutic treatment [9].

4. DATA MINING

Several tracking systems have been used to capture the critical points of the Trendelenburg gait pattern; however, they are mainly based on sport performance, tracking exercises like barbell squats. Taking into consideration that similar kinetics are used for Trendelenburg gait pattern, fundamental mechanisms of the proposed tracking systems could be applied to our case study. Research reports that camera-based tracking systems are the most accurate, nonetheless the sensitivity of such systems in terms of lighting, shadow and clutter question the system effectiveness [3]. Attempts to use microelectromechanical systems and inertial sensors have also been made, but they have proven to be prone to error due to sensor bias and measurement noise [12, 18]. In the present paper, we propose an alternative method which makes use of the ultrasound technique.

4.1 Ultrasonic sensors for positioning measurement

Advances in the research and experimental study of sensors have allowed for various protocols functioning in the infrared-radio ultra wide band (IR-UWB) channel [14, 21]. Methods due to innovative techniques in microelectromechanical system technology such as accelerometer and gyroscope have been investigated in [12, 13, 18]. Human tracking is feasible both in tri-axial and dual-axial reference systems and user movement phenomena have been mitigated with the application of the Kalman filter [17]. The transmission of the acquired empirical data is robust and accurate, however the increased complexity and cost of implementation and maintenance renders this method inappropriate for on-the-fly solutions regarding positioning measurements. In addition, path loss and multipath propagation phenomena need to be accounted for. Our application, designed for sporting areas and gymnastic halls, as well as medical centers and treatment rooms, requires the investigation of distance-dependent free space attenuation as well as large-scale (shadow) fading which contribute to the overall losses of the signal strength and the stochastic variations around its local mean [5].

As an alternate to the complex UWB method, we have chosen to apply the ultrasonic technique. This solution avoids all the intrinsic channel propagation characteristics and can be implemented independent of the nature of the topology as well as noise and interference issues. In addition, this scheme is preferred due to its low cost, safety, simplicity and high temporal resolution for low range measurement [20]. As already shown [22], the distance measurement of such an ultrasonic sensor is the returned distance reflected from the ground/surface, and the orientation of the sensor is not taken into consideration. The proposed scheme investigates a triaxial tracking system for the Trendelenburg gait pattern. The degrees of freedom and the angle of movement are also considered, from a mechanical point of view.

4.2 Sensors positioning

Having analysed the technical details of the monitoring system, it is worth mentioning that the accuracy of any human model reconstruction is strongly dependant on the extracted human silhouette [2]. We propose a 3D approach instead of 2D, so that kinematic data could be extracted with minimal error. A musculoskeletal model for gait simulation was created, inducing 80 muscle-tendon units, consisting of 41 retro-reflective markers, built of 22 articulating rigid bodies. Degrees of freedom were 20 in the lower body (six on the pelvis and seven per leg) and 17 in the torso and upper body (three on the lumbar joint and seven per arm). This model has met the fidelity criteria by comparing (i) the musculoskeletal geometry to experimental data, (ii) the simulated muscle-generated joint moments to inverse dynamics joint moments, and (iii) the simulated muscle activity to electromyography (EMG) data. It also met the speed criteria by computing the time required to generate a simulation of a single gait cycle. It is ensured that this model was as fast or faster than other frequently used models, while correcting some drawbacks that existed in previous gait models and it was implemented in the open source software platform OpenSim [23].

5. PERSONALISATION

Taking into consideration the factors discussed in the previous sections, user models can be developed to collect and utilize individuals' information either implicitly or explicitly regarding the Trendelenburg gait pattern. The adaptation types applied on the system content, behaviour and functionality, are applied through adaptation algorithms, following various approaches such as rule-based and content-based mechanisms [4]. The process of producing high-level information from a set of low-level metrics, e.g. foot position or knee joint angle, is controlled by rule-based mechanisms either implicitly or explicitly, statically or dynamically. Such rules can initialise the system and adjust it in real time by comparative and predictive models exploiting the data gathered and analysed for individuals of similar characteristics and gait. Content-based mechanisms suggest positioning, measurement and analysis of body sensors placed on individuals while walking. Such mechanisms are primarily based on the anthropometric data for each individual gathered explicitly. Factors such as body stance, straddle and walking pace should also be considered. Other mechanisms which could enhance the adaptation process include collaborative and group data analysis, e.g. people with similar anthropometric characteristics suffering from Trendelenburg syndrome, and sophisticated data mining mechanisms, including pattern discovery, rule investigation, clustering, classification, etc., implemented using Markov and probabilistic models focusing on adaptation and personalisation [19].

5.1 Personalisation of Kinetic Dysfunction

The primary aim of our system is to determine the differences between patients' motion and healthy motion. Thus, it is necessary to model and produce this healthy motion in each case. This can be done with a neuromuscular simulation model based on specific muscular and anatomical parameters, which will reproduce each patient's personalised healthy motion. Considering the difficulty to estimate these muscle and anatomical parameters, evaluating their importance for each specific movement with a sensitivity analysis is needed. Finally, validation of the simulated model's motion needs to be executed before it provides any consideration for the patient's dysfunction and Hicks et al. [11] present some ways for providing efficient solutions to the aforementioned issue. This procedure involves matching the system's anthropometric data, joint loads, muscle geometries and moment arms with a sensitivity analysis. Every part of the neuromuscular-tendon model must be separately validated against real life data derived from credible and valid tools used nowadays, such as markers, EMGs, ECGs and MRI-CT. The optimal treatment procedure an individual should adopt is recommended by the personalisation tools of the proposed framework based on the individuals' user and group context models. Therefore, the proposed personalisation approach consists of four primary sections:

- **Scenarios through rule-based and content-based mechanisms:** Capturing and formulating anthropometric, kinetic and kinematic data along with technology attributes will be used in developing and simulating scenarios, which will be then used by our framework to collect and analyse data aiming to optimise the adaptation, monitoring and recommendation process.
- **Context-aware critical situations:** In ubiquitous and pervasive computing the context model is modified and updated dynamically in real time. Our framework should adapt the changes made through context-aware reasoning and process information in real time, providing the users, e.g. patients and physiotherapists, with valuable information to complete their objectives.
- **Reproduction of personalised healthy movement:** Based on personalised patients' anthropometric and muscle-anatomical parameters, a patient specified model is produced. Blending the input data and the data derived from motion and EMG analysis of a healthy neuromuscular model, a hybrid forward-inverse dynamic model is implemented, reproducing the patients' personalised healthy movement of walking gait. The captured movement is iteratively compared with the specified model, providing recommendations by combining the mechanism of the gait pattern collector tool, recommendation engine and training process.
- **System iterative training process:** User interaction and cooperation with our framework should be exploited to understand the user behavioural and structural patterns. Therefore, the data forage, acquisition, aggregation, monitoring, reasoning and recommendation procedures should follow an iterative process which is used for system training based on its users' individual characteristics and patterns.

6. CONCLUSION AND FUTURE WORK

In this paper we proposed a personalised framework for monitoring, evaluating and recommending improvements to the Trendelenburg gait treatment process. The main challenge is to personalise the recommendations based on patients' locomotion, kinetics and anthropometrics, since they introduce important differences and limitations. The proposed framework suggests that the non-technical users i.e. patients, physiotherapists, rehabilitation experts etc. are allowed to configure the system, providing a personalised experience. The machine learning allows for system training and enhances user experience by providing more suitable recommendations. The proposed approach certainly requires practical validation in several application contexts in order to identify difficulties in the practical process and better understand the evaluation and recommendation procedure. User studies could contribute towards refining and improving the proposed framework by identifying and optimising the interplay among human mechanics, technology and information presentation through real life case studies.

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