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REVIEW ARTICLE

Nonlinearity analysis of sit-to-stand and its application: A mini-review

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ABSTRACT

The examination of human biomechanics, particularly the sit-to-stand transition, has been a focal point of research for numerous years, utilizing mathematical models of the musculoskeletal structure and motion analysis. However, researchers and scientists have encountered substantial challenges attributable to the distributed, nonlinear, and time-varying nature of this phenomenon, characterized by numerous degrees of freedom and redundancy at various levels. Conventional biomechanical assessments of human movement typically rely on linear mathematical approaches, which, while advantageous in various scenarios, often inadequately capture the predominantly nonlinear characteristics inherent in human systems. As a consequence, there has been a growing recognition of the limitations of linear methods, leading to an increased adoption of nonlinear analytical techniques rooted in a dynamical systems approach in contemporary research. Notwithstanding this trend, there exists a conspicuous dearth of a comprehensive review paper that meticulously scrutinizes these nonlinear methods and their applications across the spectrum from modelling to rehabilitation. This mini-review aims to address this gap by highlighting recent advancements in nonlinear methodologies. These methodologies have demonstrated the potential to enhance the efficacy of interventions for individuals with sit-to-stand disorders, encompassing the design of intelligent rehabilitation devices, mitigating fall risks, and facilitating early patient classification.
Keywords: Sit to stand, Nonlinear, Rehabilitation, Biomechanics.

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INTRODUCTION

The study of human biomechanics has been ongoing for numerous years (Zinkovsky et al. 1996). By employing mathematical models of the musculoskeletal structure of humans, motion analysis is conducted to enhance comprehension and refine the mechanisms of body movement. The examination of biomechanics encompasses three primary categories: sit-to-stand transitions, postural control, and gait. Among these activities, the sit-to-stand transition stands out as one of the most intricate and frequently performed tasks in an individual's daily life (Janssen et al. 2002). For instance, a physically well individual typically engages in around 65 sit-to-stand movements on weekdays and 55 on non-working days (Dall and Kerr 2010). The sit-to-stand (STS) motion occurs through the coordination of physical elements, and the central nervous system (CNS) issues movement commands based on feedback received from muscles and vestibular sensors (Matthis and Fajen 2013). The STS activity comprises four phases: (1) the flexion momentum phase, involving the rotation of the upper body, shifting the centre of mass (CoM) forward and slightly downward; (2) the transition phase between horizontal and vertical momentum; (3) the extension phase, during which the vertical component of the CoM ascends; and (4) the finalization of motion with stabilization. The most challenging moment during the sit-to-stand task occurs when the body loses contact with the chair. At this point, the posture is typically statically unbalanced, with the centre of mass (CoM) positioned behind the wheel and outside the support region (Riley et al. 1991, Gross et al. 1998).

Rising from a seated position is a crucial requirement for preserving an individual's stability by placing the vertical component of the reaction force within the support area (Rodosky et al. 1989). This action is fundamental not only for walking but also for ensuring the functional independence of the person (Lord et al. 2002, Dehail et al. 2007). There have also been reports indicating that individuals facing challenges in transitioning from a seated position to standing are at a higher risk of instability and falling while walking (Lord et al. 2002) or particularly at night when there is reduced assistance, individuals may encounter difficulties in maintaining stability when rising from bed or getting up from a chair(Bernardi et al. 2004). Especially among the elderly population, various physical issues arise, such as the gradual deterioration of muscle and cartilage tissues. These factors ultimately diminish an individual's capacity to execute the sit-to-stand movement. Furthermore, conditions like stroke, Parkinson's disease, and arthritis can significantly impair the ability to perform STS among patients (Nematollahi et al. 2019). Hence, comprehending the biomechanics of STS motion is essential for developing and evaluation techniques and rehabilitation devices (Torbati et al. 2022).

The motor control of human activities, such as the sit-to-stand motion, has proven to be a difficult task for scientists and engineers. This is due to its distributed, nonlinear, and time-varying nature, characterized by numerous degrees of freedom and redundancy at various levels. So managing and modifying this system has presented significant challenges for researchers and engineers alike. Conventional biomechanical assessments of human movement typically rely on linear mathematical approaches. While these methods may be advantageous in various scenarios, they often fall short of accurately capturing the predominantly nonlinear characteristics inherent in human systems. Consequently, nonlinear analytical techniques grounded in a dynamical systems approach have gained popularity in recent research. However, there is a noticeable absence of a comprehensive review paper that scrutinizes these methods and applications ranging from modelling to rehabilitation.

REHABILITATION

Repeatedly moving the knees can result in the deterioration of knee function for a generally healthy elderly person. Additionally, individuals with weak knees or those dealing with chronic conditions or disabilities may experience even more pronounced effects from repetitive knee movements, especially in the context of STS motion (Heidari 2011).

Modelling for rehabilitation

As previously stated, creating a STS model serves as the initial phase in developing a rehabilitation device. Simultaneously, achieving a typical STS transition necessitates synchronization between the upper and lower body movements. To elucidate the coordination dynamics inherent in a standard STS motion, it is crucial to employ a suitable model. This model plays a pivotal role in devising control and assessment techniques essential for the design of intelligent rehabilitation devices (Torbati et al. 2022). Another crucial aspect is the validation of the proposed model. A primary method involves employing the nonlinear features of the model alongside experimental data, a practice endorsed in previous studies (Nasim et al. 2021) and applied in recent years (Torbati et al. 2022). This is due to the effectiveness of the concept of dynamic similarity in establishing a suitable framework for interpreting the parallels and distinctions in locomotion. Hakkak and colleagues employed a Henon map optimized through a Genetic algorithm to develop a STS model and then proved its performance was subsequently validated by comparing extracted nonlinear features from the phase space, including the Lyapunov exponent (LE), and correlation dimension (CD) (Torbati et al. 2022). Creating a model based on experimental data sometimes can be challenging, prompting the presentation of a virtual nonlinear predictive model. This model was introduced and then contrasted with recorded data from subjects, with a focus on utilizing peak values of kinematic and kinetic results for the comparison. This model incorporates recursive Lagrangian dynamics and an optimization formulation. Its versatility extends to applications in designing exoskeletons, microelectromechanical systems for fall detection, and assistive devices in rehabilitation (Yang and Ozsoy 2020). In alternative models, researchers integrated various controllers into their nonlinear models to estimate true states. This adaptation aimed to address challenges such as noise, delays in neurofeedback from the central nervous system, and disturbances. In more detail, Linear Quadratic Regulator (LQR) and H based compensator is employed to mitigate the noise, and delay in neurofeedback of CNS and achieve natural motion (Rafique et al. 2018, Rafique et al. 2019). In addition to this, a Lyapunov-based controller was used in a linkage-based dynamic model of STS motion extracted using Lagrange's equation in the presence of sinusoidal bounded disturbances to track the desired trajectory acquired from experimental kinematic data (Nematollahi et al. 2019). In two separate studies, a nonlinear control technique grounded in feedback linearization was employed to replicate the control actions of the central nervous system during the execution of STS movements (Sultan et al. 2018, Sultan et al. 2021).

Enhancing the operational efficiency of Functional Electrical Stimulation (FES)-induced STS movements is a challenge currently under scrutiny by numerous scholars in the field. When employing FES, there are two fundamental control schemes: linear and nonlinear control methods. Research has demonstrated that the performance of the feedback linearization control (FLC) method surpasses that of the Proportional-Integral-Derivative (PID) control technique by a significant margin (Ahmed et al. 2019). So nonlinear controller is much better than linear ones for FES. Among three nonlinear controllers—Sliding Mode Control (SMC), Feedback Linearized Control (FLC), and Back Stepping Control Approach (BSC)—all schemes demonstrated strong performance. The Back Stepping Control Approach stood out as the best, exhibiting the highest Robustness to Disturbance Rejection (RDR), followed by FLC and then SMC (Ahmed et al. 2022).

Robot assistant for rehabilitation

One of important STS rehabilitation techniques is to use assistant robots, aiming to effectively help individuals stand up from a seated position using a robot manipulator. A up to dated method is proposed by Li et al. The proposed method integrates traditional model-based control, optimization, and AI-based human intention recognition. The approach involves recording human-to-human STS assistance demonstrations, extracting average intended motion trajectories for lower limb joints, and generating an optimal robot end-effector trajectory offline to minimize human joint loads. To adapt to variations in human motion, a Long Short-Term Memory (LSTM) network predicts changing intentions during STS assistance, adjusting the robot's velocity accordingly. Simulations and experiments demonstrate the algorithm's ability to minimize joint loads while following the user's intention, making it potentially applicable to home robots assisting elderly and disabled individuals in daily activities (Li et al. 2021).

Facilitation of Assistive STS Motion

Those providing assistance for STS encounter challenges, particularly in experiencing lower back pain (LBP) during the supportive movements for STS. Past research suggests that modifying the position of the feet can alleviate the lumbar load in such situations. To tackle this issue, a novel approach was suggested, involving the quantitative measurement of foot position during the STS process through the use of wearable sensors. This technique utilizes machine learning, incorporating features extracted from a solitary inertial sensor positioned on the trunk, along with shoe-type force sensors. The experimental findings indicate that the suggested approach exhibits a notable level of accuracy when compared to an optical motion capture system. Consequently, this method holds promise for measuring foot position during the supportive movements of STS, potentially leading to a reduction in LBP among caregivers (Kitagawa et al. 2021).

DETERMINATION OF FALL RISK

Emphasizing the importance of discerning the intention to prevent falls, rather than solely focusing on detecting the fall event itself, has been underscored as a critical element. This emphasis facilitates the development and deployment of intelligent devices and techniques that offer reliable support (Doulah et al. 2016). Even with the implementation of best practices in hospitals, the incidence of falls remains elevated, prompting an exploration of technological solutions to address this persistent challenge. Recent progress in addressing falls includes the application of camera surveillance and pressure sensors to identify high-risk body movements. However, it's worth noting that these approaches bring along computational complexities, latency issues, and privacy concerns. A promising alternative is found in wearable sensing devices such as inertial measurement units and accelerometers. This choice is appealing due to its cost-effectiveness, user-friendly nature, and capacity to furnish valuable information for deducing physical activities. Significantly, Sit-to-Stand (Si to St) and Stand-to-Sit (St to Si) activities have been focal points in various studies, utilizing these movements as key indicators to assess the risk of falls in older individuals (Capela et al. 2015, Ejupi et al. 2016, Pozaic et al. 2016). Furthermore, the application of technology extends to predicting fall risk in the elderly, with a specific focus on nonlinear analysis (Nasim et al. 2021). It is proven that nonlinear recurrence features for STS (Nasim et al. 2021) and virtual modelling based on recursive Lagrangian dynamics, and the optimization formulation(Yang and Ozsoy 2020) have acceptable performance for this issue.

STABILITY

In recent years, researchers have been increasingly drawing inspiration from biological systems and their self-stabilization mechanisms to design robots or robotic structures that need to uphold stability. By employing LE, computed based on experimental time series data collected for all six joints, it becomes possible to quantify the local dynamic stability of human lower limb joints during STS movements (Gibbons et al. 2019, Tarnita et al. 2021).

CLASSIFICATION

Early diagnosis plays a pivotal role in the successful treatment and mitigation of side effects for patients grappling with various diseases. The significance of timely identification cannot be overstated, as it not only enables prompt medical intervention but also enhances the overall prognosis and quality of life for individuals facing health challenges. Nonlinear analysis proves valuable in classifying patients with motor control disorders. For instance, the use of Approximate Entropy (ApEn) reveals that Parkinson's disease (PD) patients exhibit larger ApEn values compared to healthy individuals. Additionally, for PD patients, transitioning from the deep brain stimulation (DBS) off-state to the DBS on-state results in a decrease in ApEn values. Indeed, Parkinson's disease leads to an increase in the irregularity of both stand-to-sit and sit-to-stand patterns. However, the implementation of deep brain stimulation (DBS) results in a decrease in the irregularity of these patterns, rendering them more predictable (Fatmehsari and Bahrami 2011). Additionally, the classification of patients can also be achieved by assessing stability through LE (Tarnita et al. 2021).

CONCLUSION

The exploration of human biomechanics, with a specific focus on the intricate STS motion, has revealed its paramount importance in maintaining stability, functional independence, and fall prevention, especially among the elderly and those with specific health challenges. The multifaceted nature of STS motion has been dissected into phases, revealing the challenges posed during the transition from a seated to a standing position. This comprehensive understanding has paved the way for innovative approaches in rehabilitation, including the development of models, controllers, and robotic assistants. The integration of nonlinear analytical techniques, such as dynamic similarity assessments and the application of various controllers, has proven instrumental in enhancing rehabilitation strategies. The use of wearable sensors and inertial measurement units for fall risk determination offers a promising alternative to traditional methods, with a particular emphasis on nonlinear analysis. Drawing inspiration from biological systems, researchers have explored stability through LE, contributing to the design of self-stabilizing robotic structures. Furthermore, nonlinear analysis, including ApEn, has demonstrated its efficacy in classifying patients with motor control disorders, offering valuable insights for early diagnosis and improved treatment outcomes. Despite the challenges posed by the distributed and nonlinear nature of human activities, the ongoing research in biomechanics continues to unveil novel approaches that hold great promise for the development of effective rehabilitation techniques and intelligent devices. Nevertheless, the number of studies in this field is limited and needs more attention in the future.

AUTHOR CONTRIBUTIONS

All the authors have contributed equally to each of the sections of the study conducted.

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