MCIT Modeling, control & information technologies

Predictive Simulation of the Human Sit-to-Stand Transition

https://doi.org/10.31713/MCIT.2025.084

Mykhailo Tys
Department of Applied Mathematics
Lviv Polytechnic National University
Lviv, Ukraine
mykhailo.a.tys@lpnu.ua

Oleksandr Vyshnevskyi
Department of Technical Mechanics and Engineering Graphics
Lviv Polytechnic National University
Lviv, Ukraine
oleksandr.i.vyshnevskyi@lpnu.ua

Bohdan Markovych
Department of Applied Mathematics
Lviv Polytechnic National University
Lviv, Ukraine
bohdan.m.markovych@lpnu.ua

Vitaliy Korendiy
Department of Technical Mechanics and Engineering Graphics
Lviv Polytechnic National University
Lviv, Ukraine
vitalii.m.korendii@lpnu.ua

***Abstract*—The sit-to-stand transition is a fundamental human movement, the performance of which serves as a critical biomarker for functional independence, particularly in aging and clinical populations. Difficulties in executing this mechanically demanding task are associated with decreased mobility, increased risk of institutionalization, and higher mortality rates. While experimental studies have provided foundational knowledge, computational simulation has emerged as an indispensable tool for non-invasively probing the internal biomechanics and neuromuscular control strategies governing this movement. Predictive simulations, in particular, offer the unique capability to establish causal relationships between neuromuscular deficits and functional impairments, and to design and evaluate interventions in silico.**

Keywords—neuromuscular control strategy, mobility, simulation, human movement, biomechanics.

I. Introduction

The ability to rise from a chair is a seemingly simple action, yet it represents a complex and mechanically demanding task that is foundational to human mobility and independence. The sit-to-stand (STS) movement is not merely a mechanical action but a critical biomarker of an individual's functional health. Its successful execution underpins a vast range of daily activities, and its degradation is a powerful indicator of underlying neuromuscular decline. This paper establishes the profound scientific and clinical importance of studying the STS transition, framing it as a cornerstone of functional assessment and a prime target for computational biomechanical analysis.

The STS movement is one of the most frequently performed and biomechanically challenging activities of daily living (ADL) [1]. Adults rise from a seated position an average of 60 times per day, making the successful and efficient performance of this task essential for an active life [2]. The STS transition is a prerequisite for ambulation, often serving as the initiation phase for the sit-to-walk movement, which is crucial for navigating one's environment. The ability to perform an STS movement is considered a key determinant of a person's overall functional level [3]. Consequently, the inability to perform this basic skill has severe consequences. It is directly linked to a loss of independence, impaired functioning in other ADLs, and can be a precipitating factor for institutionalization, particularly among the elderly. In the most severe cases, the failure to rise from a chair is associated with an increased risk of mortality, underscoring its status as a vital sign of physiological resilience [3].

Traditional experimental studies, while foundational, have inherent limitations. They can be tedious, time-consuming, and difficult to adapt for systematic cause-and-effect analysis [4]. Furthermore, they are often restricted to measuring external variables like kinematics and ground reaction forces. Neuromusculoskeletal simulation provides a powerful complement, offering a non-invasive window into the internal biomechanics of movement. These computational models allow for the calculation of variables that are difficult or impossible to measure directly in vivo, such as the forces generated by individual muscles, the stretch of tendons, and the contact forces acting on joint surfaces [2].

The field of biomechanics is currently undergoing a significant evolution, shifting from a primarily descriptive science focused on measuring and characterizing how people move, to a predictive science capable of simulating how they will move under novel or altered conditions. Early biomechanical studies of the STS movement focused on providing kinematic descriptions of the typical movement pattern [5]. While valuable, this descriptive approach cannot explain the causal mechanisms underlying the movement or predict how it would change in response to an intervention. Predictive simulations, in contrast, can establish causal relationships between neural control inputs, muscle force-generating capacity, and overall task performance [6]. By systematically altering parameters within a validated model – for example, by simulating the effects of a specific muscle's weakness or the addition of an assistive device – researchers can conduct powerful "what-if" analyses [2]. This predictive capability is the cornerstone of modern computational biomechanics and is essential for designing targeted rehabilitation strategies, optimizing assistive technologies, and personalizing clinical treatments [7].

II. Biomechanical Foundations of the Sit-to-Stand Movement

A robust simulation of the STS movement must be grounded in a thorough understanding of its underlying physics. The execution of this task is governed by a set of well-defined mechanical principles and is highly sensitive to a range of external and internal factors. This section delves into the key biomechanical determinants that shape the STS movement, reviews the common approaches to deconstructing it into phases, and highlights a gap in methodological standardization that currently hinders progress in the field.

A. Kinematic and Kinetic Determinants

Decades of experimental research have identified several key determinants that strongly influence the strategy and success of an STS movement. These factors are not merely environmental conditions but are often used as control variables by individuals to modulate the mechanical demands of the task, ensuring that the required joint moments remain within their physiological capacity.

The three most influential external determinants are chair seat height, the use of armrests, and the position of the feet [3]: chair height, armrest use, foot position.

The height of the seat has a profound impact on the joint moments required for the transition. Using a higher chair seat can reduce the peak extension moment required at the knee by up to 60% and at the hip by up to 50%.3 Conversely, lowering the chair seat substantially increases the muscular demand, forcing an individual to either generate greater momentum through more vigorous trunk flexion or to reposition their feet posteriorly to gain a mechanical advantage [3]. For individuals with muscle weakness, such as the elderly, a low chair can make the task impossible without compensation.

The use of armrests provides a direct way to offload the lower limbs. Pushing off with the arms can reduce the required hip extension moment by as much as 50%, effectively supplementing the force generated by the leg extensors [3].

The anteroposterior position of the feet relative to the chair is a critical strategic variable. Repositioning the feet posteriorly (i.e., tucking them further under the chair) dramatically reduces the horizontal distance between the body's center of mass (COM) and the ankle joints at the point of lift-off. This change in leverage significantly decreases the required hip extension moment. One study documented a reduction in the maximum mean hip extension moment from 148.8 N·m to just 32.7 N·m when the foot position was shifted from anterior to posterior [3].

In addition to these external factors, the manner in which the movement is performed – specifically its speed and smoothness – also dictates its biomechanical characteristics. The stand-to-sit (StandTS) movement, which involves eccentrically controlling the body's descent, is particularly sensitive to these variables. Slower and smoother StandTS movements demand greater controlled eccentric work from the knee and hip extensor muscles to absorb and manage the body's falling momentum. This increased muscular control is associated with reduced postural sway, indicating enhanced stability [8].

B. Phasic Deconstruction of the STS Movement

To facilitate analysis, the continuous STS movement is typically deconstructed into a series of discrete phases. This partitioning allows researchers to isolate and study specific biomechanical events and neuromuscular strategies. The most frequently cited framework is the four-phase model proposed by Schenkman and colleagues [3]:

1) Phase I (Flexion-Momentum). This preparatory phase begins with the initiation of movement and is characterized by the forward flexion of the trunk. This action serves to move the body's COM forward, positioning it over the base of support (the feet) in anticipation of lift-off. This phase concludes at the instant just before the buttocks are lifted from the seat.

2) Phase II (Momentum-Transfer). This phase begins with "seat-off", the moment the buttocks leave the chair. The horizontal momentum generated during Phase I is transferred into vertical momentum to lift the body. This is a critical and unstable phase of the movement. It ends when the ankle joint reaches its maximal dorsiflexion angle.

3) Phase III (Extension): This phase begins just after maximum ankle dorsiflexion. It is characterized by the coordinated extension of the hip and knee joints, which raises the body's COM to its highest point. The trunk also extends to an upright posture. This phase concludes when the hips cease to extend.

4) Phase IV (Stabilization). In this final phase, any remaining oscillations are dampened as the body achieves a stable standing posture.

While the four-phase model is widely used, it is not the only one. Other researchers have proposed models with two, three, or five phases, depending on the specific research question and measurement techniques employed [9]. The simplest deconstruction involves just two phases, using the single event of seat-off as the demarcation point between the preparatory phase and the rising phase [10].

III. RESULTS AND DISCUSSION

A. *Results of Studying the Sit-to-Stand Movement*

The plot in Fig. 1 shows synthetic hip, knee, and ankle joint angles over a 3-second sit-to-stand. Hip and knee extend smoothly from a seated posture toward full extension; the ankle changes modestly, reflecting a relatively smaller range of motion in this simplified scenario. Hip extension starts around a seated angle (about 90°) and increases smoothly toward standing, mirroring the trunk's forward lean followed by strong hip extension. The smooth S-shape suggests a controlled acceleration and deceleration, typical of comfortable-speed STS. Knee extension follows a similar trajectory to the hip, reflecting coordinated extensor action. In many real trials, knee extension peaks slightly after hip extension onset as people "release" the seat; the plot captures the overall rise to full extension without abrupt transitions. Ankle behavior shows a modest increase and stabilization, consistent with mild dorsiflexion near seat-off and limited plantarflexion near the end. In some cases, ankle excursions can be larger with low seats, fast rises, or balance-challenging conditions.

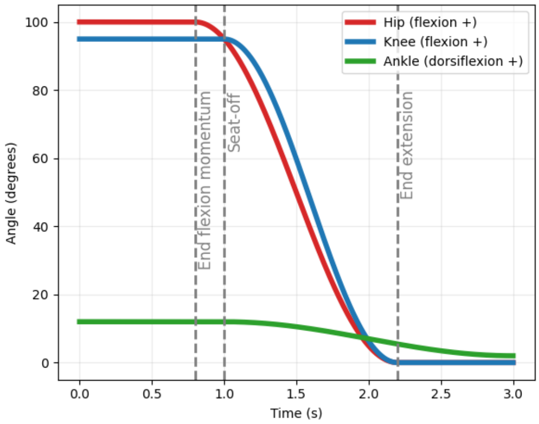

Figure 1. Sit-to-stand joint angles over time (flaxion positive convention)

B. *Biomechanical Insights*

People typically generate forward momentum with trunk flexion, then transfer momentum vertically at seat-off via hip and knee extensors. The ankle modulates the center of pressure for balance.

Forward trunk lean reduces the horizontal distance between center of mass (COM) and feet, minimizing required knee torque at seat-off. A delayed or insufficient lean often increases knee demand.

Hip and knee show the largest extensor moments and peak power during momentum transfer. Ankle contributes to balance and subtle propulsion rather than primary lifting.

Prolonged knee flexion, reduced hip extension range, or excessive ankle strategy can indicate weakness, pain avoidance, or balance impairment. Asymmetries between legs or irregular velocity profiles may reveal compensation patterns.

C. *MapleSim Model of the Human Lower Limbs*

The MapleSim environment allows for representing the human lower limbs as a multibody system with joints, rigid segments, and control inputs.

The model includes the foot, shank, thigh, and pelvis, each defined as a solid body with appropriate geometric and mass properties. These segments are assembled in the sagittal plane to reproduce the anatomical arrangement of the ankle, knee, and hip joints. By constraining the degrees of freedom of each joint to flexion and extension, the model captures the essential kinematics of the lower extremities during functional tasks such as sit-to-stand or gait.

The hip joint is modeled as the connection between the pelvis and the femur, allowing controlled rotation that simulates hip flexion and extension. The knee joint links the femur and tibia, reproducing the hinge-like motion of the quadriceps mechanism. The ankle joint connects the tibia to the foot segment, enabling dorsiflexion and plantarflexion. Each joint can be driven by torque actuators or prescribed motion profiles, allowing the simulation of muscle forces and coordination strategies. The use of MapleSim software enables the calculation of joint angles, angular velocities, and reaction forces, which can then be compared with experimental biomechanical data.

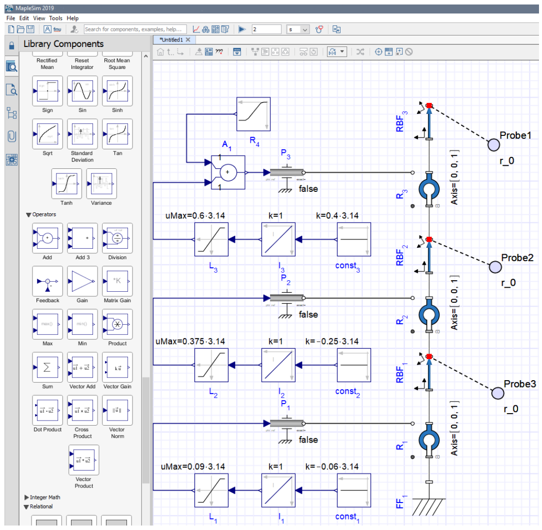

Figure 2. MapleSim model of the human lower limbs

The model also incorporates reference planes and markers that represent anatomical landmarks, such as the hip center, knee axis, and ankle axis. These markers allow the trajectories of the joints and the center of mass of the trunk to be visualized relative to the initial seated posture. The structural alignment of the tibia, femur, and spine in the sitting position serves as the baseline configuration, from which the dynamic transition to standing is simulated. By analyzing the resulting motion paths, researchers can study the coordination of the lower limbs, the distribution of joint torques, and the strategies used to maintain balance.

Through this MapleSim representation, the lower limb system becomes a virtual prototype that can be adapted to different anthropometric parameters, seat heights, or movement speeds. It provides a powerful tool for exploring the biomechanics of human movement, supporting applications in rehabilitation engineering, prosthetics design, and the study of pathological gait or sit-to-stand impairments.

D. Simulation of the Sit-to-Stand Process

Fig. 2 illustrates the trajectories of three key body landmarks during the sit-to-stand transition. The red, blue, and green curves correspond to the knee, hip, and trunk's center of mass, respectively, plotted within the vertical (sagittal) plane. Each curve traces the displacement of the respective point from the initial seated posture through to the final upright stance. The black reference line denotes the initial (boundary) structural alignment of the tibia, femur, and spine in the sitting position, serving as a baseline against which subsequent motion can be evaluated. The forward and downward excursion of the hip and trunk's center of mass prior to seat-off reflects the flexion-momentum phase, during which the body shifts its center of mass over the feet. The subsequent upward and posterior arcs of the hip and trunk curves indicate coordinated extension of the hip and knee joints, while the knee trajectory demonstrates a forward-then-upward path consistent with shank inclination followed by knee extension. The relative compactness of the knee and hip paths compared to the larger excursion of the trunk's center of mass highlights the role of proximal joint extension in elevating the body. Together, these trajectories capture the sequential strategy of momentum generation, transfer, and stabilization that characterizes a typical sit-to-stand movement, and they provide a spatial reference for analyzing joint coordination, balance control, and potential deviations in clinical populations.

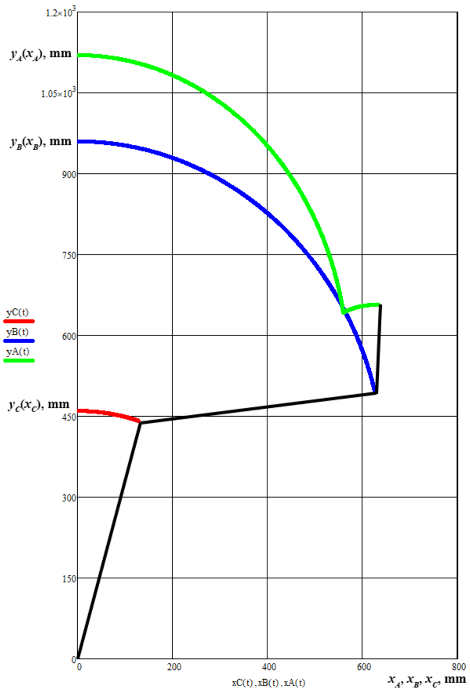

Figure 3. Motion paths of the three key body landmarks during the sit-to-stand transition: red curve – knee point; blue curve – hip point; green curve – trunk's center of mass

IV. CONCLUSIONS

This paper has underscored the sit-to-stand transition as a critical biomarker of functional independence and has demonstrated the utility of predictive simulation as a tool for its biomechanical analysis. The STS movement, while fundamental to daily living, is a mechanically demanding task whose degradation is linked to significant declines in mobility and quality of life, particularly in aging and clinical populations.

Through a review of the foundational biomechanics, key determinants such as chair height, armrest use, and foot position were identified as critical modulators of the task's mechanical demands. The development and simulation of a multibody model of the human lower limbs in MapleSim reproduced the characteristic kinematics of the STS movement. The visualized trajectories of the hip, knee, and the trunk's center of mass provide a clear quantitative representation of the complex coordination strategy, aligning with the established sequential phases of flexion-momentum, momentum transfer, extension, and stabilization.

The results affirm that computational modeling provides a powerful, non-invasive method to probe the internal dynamics of this fundamental movement. Such models serve as a virtual prototype for conducting "what-if" analyses, which are essential for designing targeted rehabilitation strategies, optimizing assistive technologies, and personalizing clinical treatments for individuals with impaired mobility.

REFERENCES

[1] J. Li *et al.*, "Kinematic analysis of the human body during sit-to-stand in healthy young adults," *Medicine (Baltimore).*, vol. 100, no. 22, p. e26208, Jun. 2021, doi: 10.1097/MD.0000000000026208.

[2] E. van der Kruk and T. Geijtenbeek, "A planar neuromuscular controller to simulate compensation strategies in the sit-to-walk movement," *PLoS One*, vol. 19, no. 6, p. e0305328, Jun. 2024, doi: 10.1371/journal.pone.0305328.

[3] W. G. Janssen, H. B. Bussmann, and H. J. Stam, "Determinants of the sit-to-stand movement: A review," *Phys. Ther.*, vol. 82, no. 9, pp. 866–879, Sep. 2002, doi: 10.1093/ptj/82.9.866.

[4] B. Ozsoy and J. Yang, "Simulation-based unassisted sit-to-stand motion prediction for healthy young individuals," in *Volume 6: 10th International Conference on Multibody Systems, Nonlinear Dynamics, and Control*, American Society of Mechanical Engineers, Aug. 2014. doi: 10.1115/DETC2014-34231.

[5] S. Nuzik, R. Lamb, A. VanSant, and S. Hirt, "Sit-to-stand movement pattern," *Phys. Ther.*, vol. 66, no. 11, pp. 1708–1713, Nov. 1986, doi: 10.1093/ptj/66.11.1708.

[6] R. R. Neptune, C. P. McGowan, and S. A. Kautz, "Forward dynamics simulations provide insight into muscle mechanical work during human locomotion," *Exerc. Sport Sci. Rev.*, vol. 37, no. 4, pp. 203–210, Oct. 2009, doi: 10.1097/JES.0b013e3181b7ea29.

[7] T. K. Uchida, A. Seth, S. Pouya, C. L. Dembia, J. L. Hicks, and S. L. Delp, "Simulating ideal assistive devices to reduce the metabolic cost of running," *PLoS One*, vol. 11, no. 9, p. e0163417, Sep. 2016, doi: 10.1371/journal.pone.0163417.

[8] D. Cabrera and K. Smith, "The influence of smoothness and speed of stand-to-sit movement on joint kinematics and kinetics during stand-to-sit," *International Journal of Exercise Science: Conference Proceedings*, vol. 2, no. 16, Art. 57, 2024.

[9] C. Pinheiro *et al.*, "Kinematic and kinetic study of sit-to-stand and stand-to-sit movements towards a human-like skeletal model," in *2019 IEEE 6th Portuguese Meeting on Bioengineering (ENBENG)*, IEEE, Feb. 2019, pp. 1–4. doi: 10.1109/ENBENG.2019.8692569.

[10] C. V. Mihova, "Sit-to-stand biomechanics: A systematic review," M.S. report, Dept. Kinesiology and Health Education, Univ. of Texas at Austin, Austin, TX, 2021 [Online]. Available: https://repositories.lib.utexas.edu/items/f2284fee-d008-4e98-837a-650203c27efb.