Communication

Optimum Handle Location for the Hand-Assisted Sit-to-Stand Transition: A Tool

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Abstract: Background: The aging process contributes to the decline in physical capacity that leads to loss of independence in performing life activities. Immobility and instability are the most significant predictors and indicators of physical disability and dependence. As a result, a variety of assistive devices exist to address immobility and instability in older adults, including walkers, canes, crutches, wheelchairs and handrails. Sit-to-stand (STS) transitions are the most common transitions in daily mobility activities. The ability to perform STS transitions successfully is therefore one of the most important activities to focus attention on. As a result of physical deterioration, older adults will sooner or later be faced with their physical limitations, and in particular, will not be able to provide enough torque at critical body joints to make the STS transition. Aim: This paper suggests employing two-arm assistance using two handles located symmetrically in the body's sagittal plane. During the aging process, people are faced with varying levels of muscle deterioration and body constraints and consequently require different levels of assistance to complete the transition successfully. This paper aims to develop a tool to find the optimum handle location for people based on their body constraints to reduce knee torque (identified as the critical joint in the STS transition). These findings are also used to measure the effects of assistive device handle position on the biomechanics of the two-arm assisted STS transition. Methods: For this purpose, a theoretical tool was developed by integrating human body kinetics with a multi-objective genetic algorithm to find the optimum hand force required at the seat-off point for a set of potential handle locations. The tool was set to achieve the minimum knee torque within the defined body constraints and assumptions. In line with the physics of the STS transition, the "seat-off point", when subjects lose their seat support, was chosen as the most challenging point of the task. This was coupled with the "nose over toes" posture recommended to older adults by occupational therapists. Results and Discussion: The schematic of the developed tool shows that the best handle locations requiring the minimum torques at the body joints are positioned in handle zone 2, where the handles are placed vertically above the knee and below the hip joints and horizontally located ahead of the hip and behind the knee joints. Within this handle zone, both components of the hand forces (vertical downward and horizontal backward) provide assisting torque to all the body joints and consequently reduce the torques required at body joints.

Keywords: assistive devices; STS transition; aging process; independence of living

1. Introduction

The aging progress is linked to increasing demands for acute health care services, growing chronic impairments, and sometimes, a need for continuous caring assistance [1]. The main goal of aged care is to maintain the ability of older adults to carry out their basic daily activities such as toileting, bathing, eating, and transferring out of bed and chair independently. The ability to perform daily activities without assistance is fundamental to an independent life [2,3]. People who are unable to carry out their daily activities rely on others for assistance, threatening their life independence. Research has consistently shown

that loss of independence in basic activities of daily living (ADLs or BADLs) is strongly correlated with institutionalisation, carer burden, loss of resources and death [4–7].

The STS transition is known as the foundation for other daily activities. Any level of disability in performing this transition threatens independence of living not only among older adults but also among young adults and even children. For a successful transition, enough strength is required in the body muscle groups to provide torque at the hip, knee and ankle joints such that the body's CoM can be moved from a sitting posture to an upright standing posture. Additionally, the STS transition is shown to be an indicator of falls among older adults. More than 50% of health expenses for older adults in New Zealand are fall-related [8].

Relatively few studies have measured the biomechanics of two-arm assisted STS transitions. Kinetic calculations have shown that arm assistance reduces torque in the hip joint by 50% [9]. Smith et al. [10] measured the effect of armrests on STS transitions in young people, middle-aged adults and older adults. Older subjects recorded significantly lower knee extensor and joint forces compared with young subjects when not receiving armrest assistance. Older adults recorded a higher contact force in the shoulder joints when using armrests.

The seat-off point is the critical point of transition when maintaining posture is most difficult and a large load is being tolerated by the lower limbs [11]. Studies have analysed the functionality of lower limbs during the STS transition and identified the peak torques required in the lower limb joint at the seat-off point [12–14].

Of the lower limb joints, the knee plays the most significant role in the STS transition and may provide up to 70% of the work to complete the task [15]. It has been shown that during the STS transition, knee extensors provide 72% of concentric force at the hip and knee. Knee extension force has been found to be an indicator of STS transition independence both in older adults [16–24] and in highly impaired patients [23,25–27]. In this regard, minimising the knee torque requirement is the main concern in an STS transition.

Study Aim

During the aging process, older adults are faced with muscle deterioration in different muscle groups. During this degeneration, older adults reach a point where the strength of the calf muscles is just less than the strength required to generate knee torque to lift the bottom off the seat and complete the STS transition.

This study suggested receiving two-arm assistance to compensate for lower limb degeneration by utilising symmetrical handles in the sagittal plane for a more symmetrical and stable transition. People experience the aging process with different levels of severity and body constraints to deliver enough torques in the body joints to complete the STS transition successfully. For this purpose, this paper aims to develop a tool to find the optimum handle location at the seat-off point (the most critical point of the transition) for people with different body constraints.

2. Materials and Methods

In order to measure the effect of different handle locations on reducing knee torque, a theoretical tool (Figure 1) was developed by integrating an optimization technique (Genetic Algorithm) with the equilibrium equation for the above-knee body.
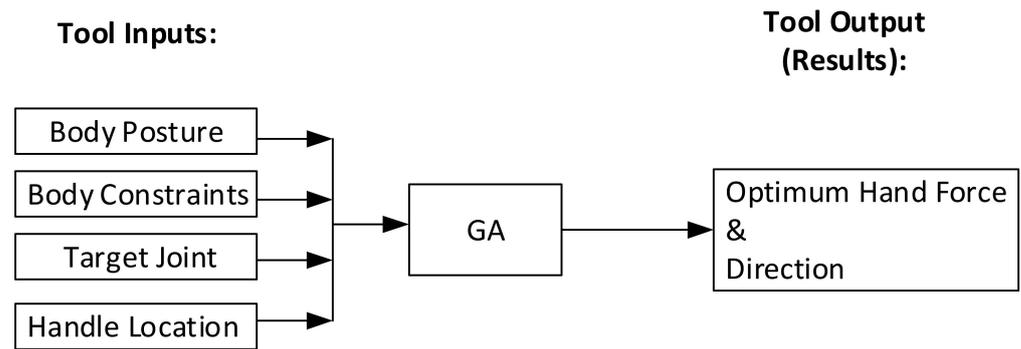
Figure 1. Schematic of the developed tool.

2.1. Kinetic Model Derivation

To ensure the safety of the transition, momentum was not considered and subjects were required to perform the transition as steadily as possible. In this regard, the force equilibrium equations along the X and Z axes, in addition to the torque equilibrium equation around the Y axis, needed to be derived for rigid bodies (each body made of several different body segments) to obtain the torques.

2.1.1. Hip Torque Calculations

To calculate torque at the hip joint, the thigh is assumed to be fixed in space as shown in Figure 2.
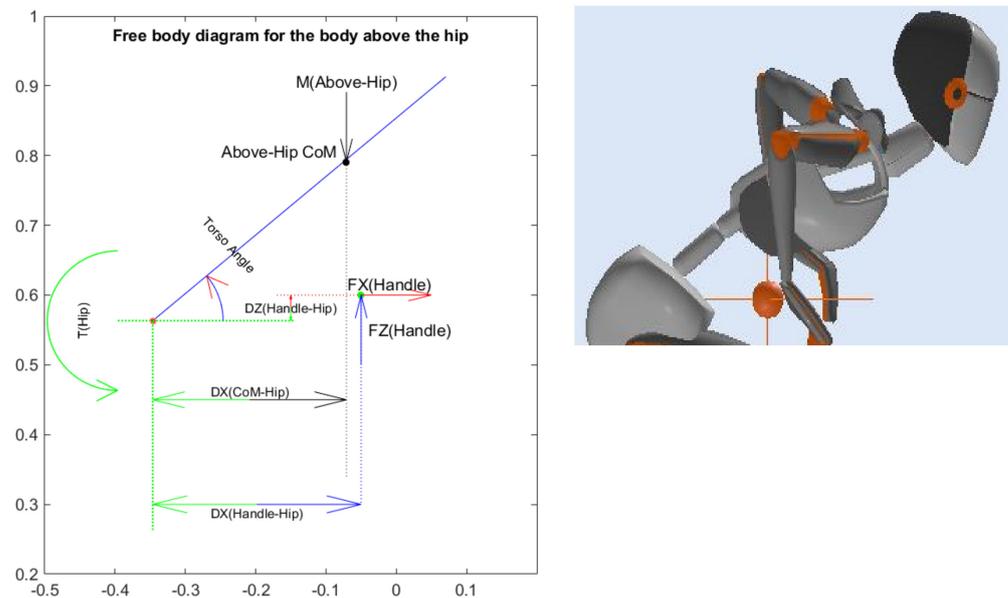
Figure 2. Free body diagram of the body above the hip (head and arms are not shown); m and T represent mass and torque, respectively.

The torque of the hip joint was calculated by employing the equilibrium equations on the free body diagram of the body above the hip, as shown in Figure 2:

$$T_{Hip} = -m_{Above\ HipBody} * DX_{CoM-Hip} + Fz_{Handle} * DX_{Handle-Hip} - Fx_{Handle} * DZ_{Handle-Hip} \tag{1}$$

The mass used in Equation (1) is the mass of the upper body.

2.1.2. Knee Torque

During the STS transition, the knee joint must compensate for the effect of body mass on the knee joint. To calculate torque generation at the knee joint, the lower leg is assumed

to be fixed in space so as to examine only the torque generated in the knee joint, as shown in Figure 3.
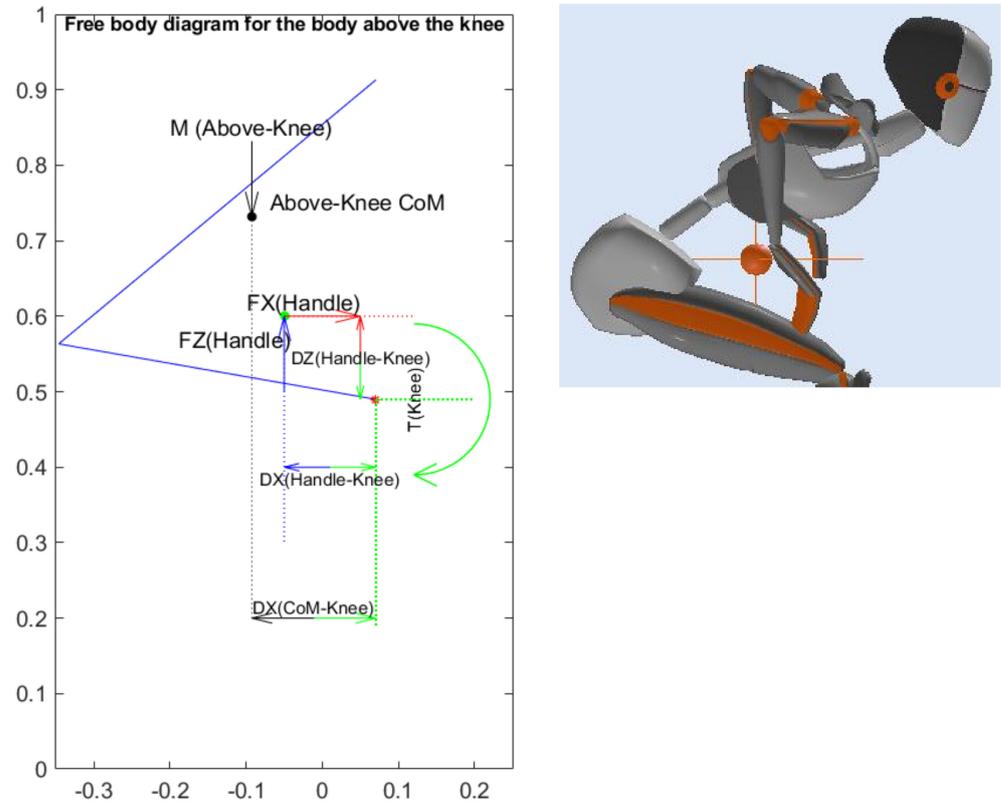
Figure 3. Free body diagram of the body above the knee (head and arms are not shown); m and T represent mass and torque, respectively.

The torque at the knee joint was calculated by employing the equilibrium equations on the free body diagram of the body above the knee, as shown in Figure 3:

$$T_{Knee} = m_{Above\ KneeBody} * DX_{CoM-Knee} - Fz_{Handle} * DX_{Handle-Knee} - Fx_{Handle} * DZ_{Handle-Knee} \qquad (2)$$

The mass used in Equation (2) is the mass of body above the knee.

The green curved arrow in Figure 3 shows the positive direction of the knee torque. The torque induced by the body mass on the knee joint is anticlockwise (shown using black arrows). Both vertical and horizontal handle forces (FZ and FX), shown using blue and red arrows, provide anticlockwise assisting torque to the knee joint and consequently reduce the torque required of the muscles at this joint (shown using blue and red curved torque arrows at the knee joint).

2.1.3. Ankle Joint Calculations

The ankle joints play a significant role not only in the STS transition but in almost all body activities. The ankle joint is responsible for maintaining balance during any body motion when interacting with the ground, especially when standing.

The torque and reaction forces at the ankle joint were calculated by employing the equilibrium equations on the free body diagram of the body above the ankle shown in Figure 4:

$$T_{Ankle} = -m_{AboveAnkleBody} * DX_{CoM-Ankle} + Fz_{Handle} * DX_{Handle-Ankle} + Fx_{Handle} * DZ_{Handle-Ankle} \qquad (3)$$

The mass used in Equation (3) is the mass of the body above the ankle.
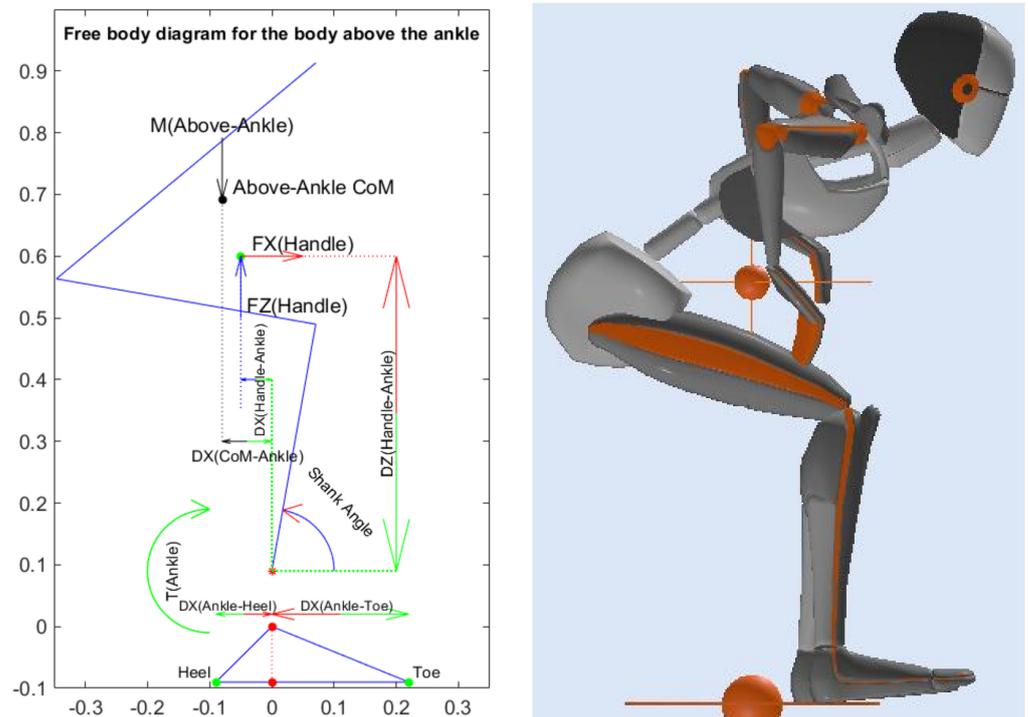
Figure 4. Free body diagram of the body above the ankle (head and arms are not shown); m and T represent mass and torque, respectively.

2.2. Optimization Plan

This study identified the knee joint as the most limiting factor in the STS transition. In this regard, minimising the knee torque required is the main concern.

2.2.1. Objective

The target is to find the minimum components of hand force required to minimise the knee torque the subject has to provide for STS transition at the seat-off point. This target is represented by two objective functions:

The first objective function was calculated to minimise the resultant hand force as:

$$Objective\ function\ 1 = F(Resultant)_{Hand\ Force} = \sqrt{Fx_{Hand\ Force}^2 + FZ_{Hand\ Force}^2} \quad (4)$$

The second objective function was calculated using Equation (5) to reduce the knee torque required as:

$$Objective\ function\ 2 = T_{Knee} = m_{Above\ KneeBody} * DX_{CoM-Knee} - Fz_{Handle} * DX_{Handle-Knee} - Fx_{Handle} * DZ_{Handle-Knee} \quad (5)$$

2.2.2. Proposed Constraints and Assumptions

The constraints and assumptions encountered while performing the optimization process are as indicated below:

1. Assume balance is essential.
    The ankle joint is responsible for maintaining balance during any body motion when interacting with the ground, especially when standing. Ankle torque is conceptualized as acting with vertical and horizontal forces at different points along the foot (from heel to toe) in reaction to the ground (shown in Figure 4). In this regard, there are clearly defined limits to the application of ankle torque:

$$-m_{AboveAnkleBody} * DX_{Ankle-Heel} < T_{Ankle} < m_{AboveAnkleBody} * DX_{Ankle-Toe} \quad (6)$$

2. Assume the maximum available knee and hip torques occur when the subject can just hold the seat-off posture with hands on knees. This was calculated at 5.4 Kgm for each knee joint for the subjects who were tested.
3. Assume that hip torque cannot be more than 7.36 Kgm (the maximum available hip torque noted in assumption 2 above):

$$T_{Hip} < 7.36 \text{ Kgm} \tag{7}$$

4. The seat-off posture employed for the theoretical tool developed in this study was based on the nose-over-toes or full trunk flexion strategy (as shown in Figure 5), where:
   a. The torso angle is 40°
   b. The upper leg angle is 177° (the knee is above the hip)
   c. The shank angle is 87° from the horizontal position (the knee is in front of the ankle)
5. Assume the hand assistance force is the result of vertical and horizontal forces, as expressed in Equation (4).
6. Assume (based on analysis) that each hand can provide a maximum of 20 Kg resultant force:

$$F(Resultant)_{Hand\ Force} < 20 \text{ Kg} \tag{8}$$

7. The potential handle locations are accessible.
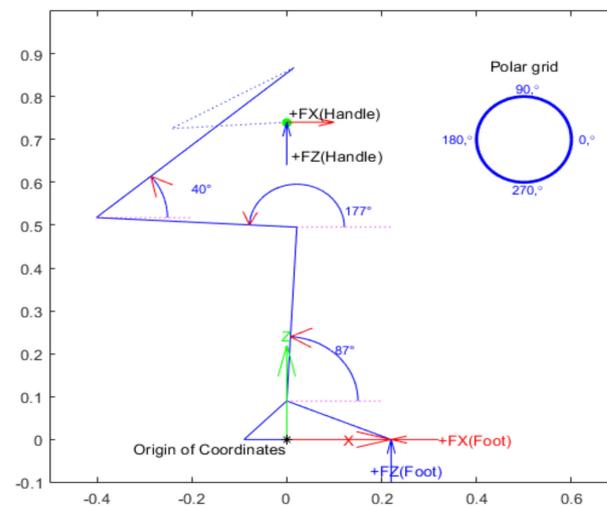
Figure 5. Seat-off posture employed in the theoretical tool.

2.2.3. Definition of Optimum Handle Position

The optimum handle position has the smallest resultant handle force required to achieve the minimum knee torque requirement. In this regard, the theoretical tool developed in this study used the knee joint as the target joint to reduce its torque requirement while maintaining the torque requirements at the hip and ankle joint within the limits.

3. Results

Figure 6 shows the minimum hand force needed to achieve minimum knee torque at the seat-off point by taking balance into account for a subject with a weight of 76 Kg. Balance is achieved by a combination of hand force and ankle torque. The range of ankle torque is limited by muscle strength and foot size. For this purpose, it is assumed that ankle torque is enough for the person to stand on the heel or toe of both feet at once. In this regard, the position of the ground reaction force needs to be within the length of the foot.
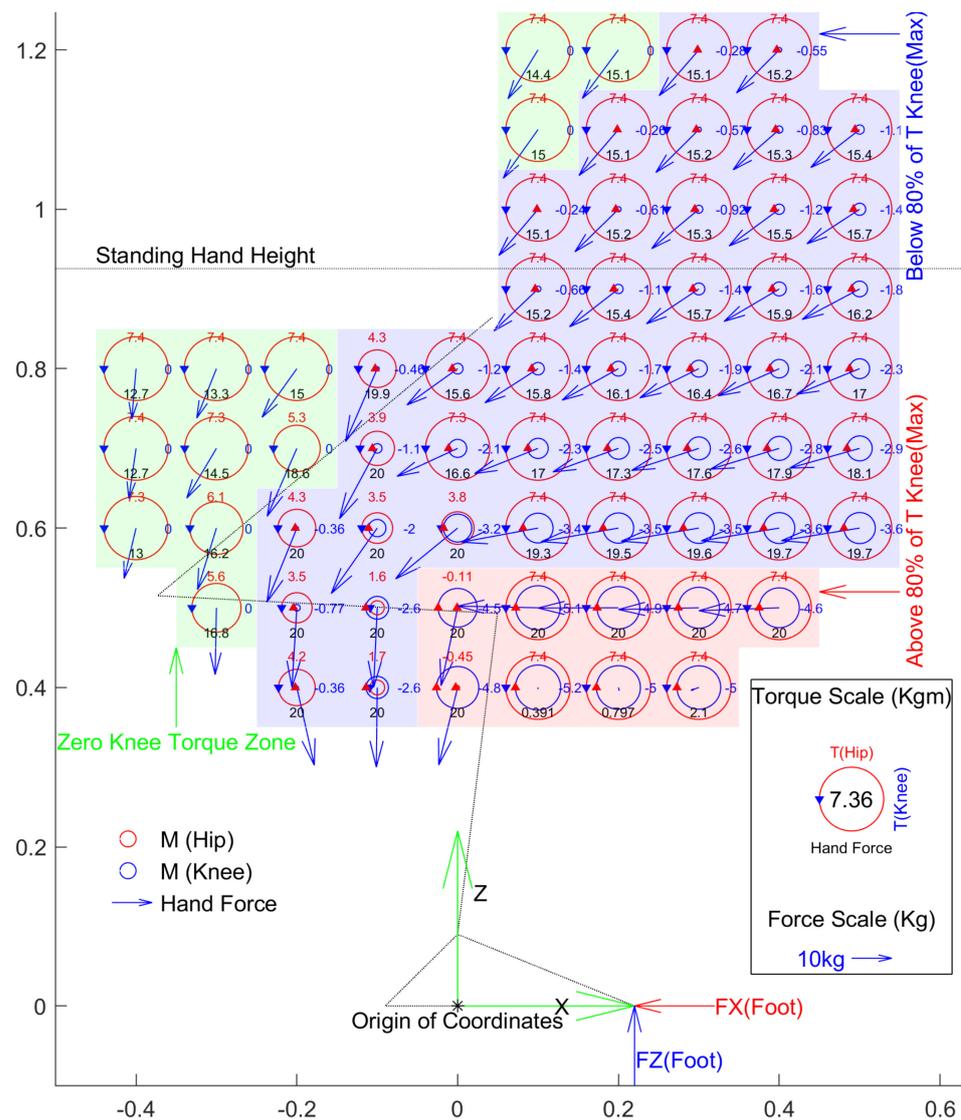
Figure 6. The minimum hand force required to achieve zero knee torque with no other constraint. (Note that the numbers around the circles are values for hand force (black), knee torque (blue circle) and hip torque (red circle), as shown in the key. The subject is shown in dotted black lines at the seat-off position (head and arms are not shown). Potential handle positions are shown in the sagittal (XZ) plane indicated. The resultant hand force required from each of the two hands to achieve zero knee torque is shown by straight blue and green arrows at each location. Green arrows show that while minimum hand force is achieved, balance is not achieved at this handle location. The size of the circle represents torque magnitude compared with the scale on the bottom right. The torque direction is shown by arrowheads on the circle, blue for anticlockwise and red for clockwise. Three coloured zones are shown: green with zero knee torque, blue with knee torque below 80% of maximum, and red with knee torque above 80% of maximum.

3.1. Limitation of Handle Zone

The handle locations shaded in red (shown in Figure 6) reduced the knee torque by 20%. These handle locations require the largest hip torques due to the required upward vertical hand forces. Consequently, these handle locations are excluded from the potential handle locations.

3.2. Handle Zones

The locations of handles can be divided into different zones based on the position of body joints. During the STS task, as the body joints are positioned in different places, hand force application can assist or oppose the body joints. Each component of hand force can provide clockwise or anti-clockwise torque depending on the handle location in any of the 4 quadrants around the joint. Figure 7 was derived to summarise the directions of each component of hand force that provides assisting torque to the knee (clockwise), hip (anti-clockwise) and ankle (clockwise) joints, reducing the torque requirements at these joints.
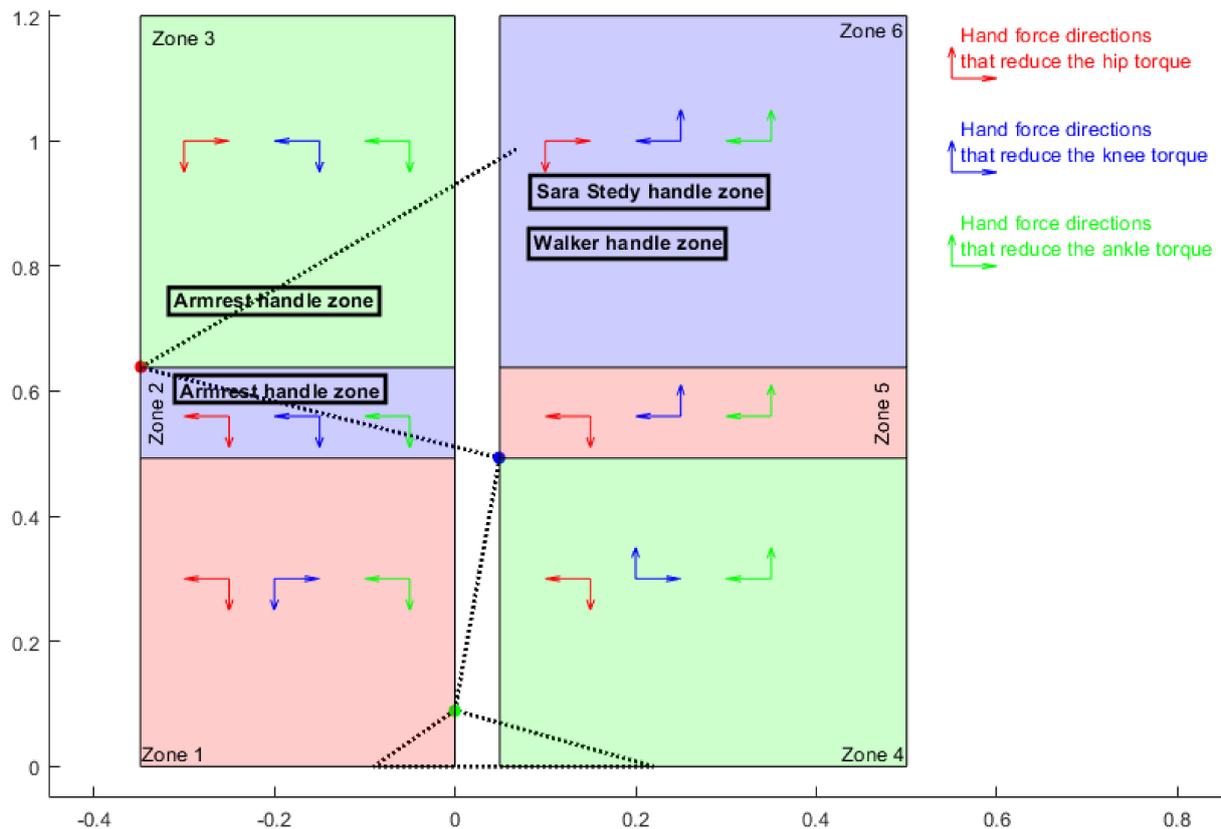
Figure 7. Handle location zones (arrows show the hand force directions that reduce torque at the knee, hip and ankle joints).

Arrows in each zone show the contributing directions of each component of hand force providing assisting torque to the hip, knee and ankle joints (blue for knee, red for hip and green for ankle). For example, for a handle placement in zone 1, backward horizontal hand force reduces hip and ankle torque while increasing the knee torque requirement. In addition, within this zone, applying downward vertical hand force assists the hip, knee and ankle joints and reduces torque requirements in both joints.

4. Discussion

There are few analyses of two-arm assisted STS transitions in older adults. Most of these studies measured the effect of a fixed handle location on the biomechanics of the STS transition [10,28,29] and have not measured the effect of different handle locations. There is only one study, by Kinoshita [30], that measured the effect of handrail height at two different heights and showed that the combined high and low positions recorded the minimum physical load required during STS transition. These papers used handrails at a fixed height and took the effect of grip position and trunk-tilt angle into account. Xiaolong Han and Xue [14] is the only study that has measured the effect of two grip positions and

trunk-tilt angles at the seat-off point and found that the minimum knee torque occurred with a trunk-tilt angle of 30 degrees and grip positioned above the greater trochanter beneath the chest.

In summary, all research on two-arm assisted STS transition has concentrated on biomechanical comparisons of a specific group of subjects in real-life in reaction to the limited fixed handrails. None of the studies have looked at finding the optimum handle location for an individual. This study developed a theoretical tool that enables us to identify the best handle location for a specific individual based on their body constraints (e.g., maximum available hip/knee/ankle torques, hand force limit) to receive the optimum hand assistance at the critical or challenging point the person is faced with (e.g., seat-off point, initiation point).

The tool developed in this research focuses on the study of the biomechanics of transition at the seat-off point, which is typically the most difficult point of transition.

However, this means that the study does not include the required body strength and motion for the whole transition.

The kinetic parameters studied in this research were limited to the required torques at the body joints at a defined seat-off posture. These kinetic parameters do not represent the required power, not only at the defined point but also during the whole transition.

The optimum hand location in this study was assumed to be fixed during the whole transition, although the body's CoM is continually moving during the transition. Having an adjustable handle, or multiple handle locations, could help to compensate for the moving CoM during the transition. This study has not addressed these issues and they are left for future studies.

4.1. Contribution of Assistive Devices to the STS Transition

Figure 7 also shows the handle locations of some of the available assistive devices.

The kinetic parameters of these handle locations at the seat-off point are normalised by body mass (BM) in Table 1.

Table 1. Seat-off kinetics for the handle locations provided by assistive devices.

Devices	F_X (% *of BM*)	F_Z (% *of BM*)	T_{Knee} (% *of BM*)	T_{Hip} (% *of BM*)
Walker	17.39	11.2	1.9	9.7
Armrest	9.7	22.4	0	7–9.7
Sara Stedy	14.4	13.8	0.8	9.7

Assistive devices deliver different levels of hand assistance to users depending on handle placement. Comparing the use of armrests on standard chairs, walkers and Sara Stedy showed that chair armrests provide the most assistance.

4.2. Recommended Future Work

In general, the following could be considered for future research:

- Make available a user-friendly tool or app that allows practitioners to produce handle location maps for individual patients.
- Examine the best handle position for the whole STS transition, not just the seat-off point and consider adjustable handle locations over the whole transition to find the optimum handle trajectory.
- Validate the current tool map with real patients and real handle positions through experimental set-up.
- Validate the current tool map for people with particular weaknesses.
- Employ the tool to study the contribution of different assistive devices to people with particular strengths.

5. Conclusions

The best handle locations requiring the minimum torques are placed in handle zone 2 (see Figure 7). Within this zone, the assisting directions of both horizontal and vertical hand forces to the ankle, hip, and knee joints are the same: vertically downward and horizontally backward. This means that, with handle placements in this zone, subjects can get assistance from both vertical and horizontal components of hand forces for all joints. The best handle location is zone 2, requiring the minimum torques at the body joint horizontally placed between 0.3 m and 0.1 m behind the ankle and vertically 0.5 m above ground level.

Seat and armrest support can be used as handle locations at this point. However, although the seat-off point is the most challenging point of transition, it is not the only failing point that people might face during the task, and it is worth noting that the highlighted handle locations become inaccessible as the person rises, and so do not contribute to task completion past the seat-off point. The tool developed in this study enables us to examine additional failing points (postures) for each person so as to find the best handle locations.

The tool developed in this study can be practically used by medical staff, especially occupational therapists, to find the best handle location and handle zone for their patients based on their body constraints and strengths.

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