Evaluating the Influence of Different Sit-to-Stand Strategies on the Biomechanics of the Upper Extremity Dependent on Age and Sex.

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Introduction: *During the sit-to-stand (STS) motion, thigh push-of (TP) is frequently used, yet the biomechanical advantage for the upper extremity, is relatively unknown. In this thesis, the STS motion is analyzed for three different techniques; TP, armrest push-off (AP), and no arm aid (NA). The aim of this study is to determine the biomechanical advantage of the TP strategy through examining the joint moments (JM), and muscle forces (MF). Furthermore, the study aims to find whether age or gender affects the JM and MF generated in the TP, AP, and NA strategies.* ***Method****: Time to stand (TTS), JM and MF exerted on the upper extremity were examined for TP, AP and NA strategies for 34 participants across 3 groups: EM, elderly female (EF), and young males (YM). The metrics were obtained through inverse kinematic (IK), inverse dynamic (ID), and static optimization (SO) simulations in a 3D musculoskeletal model.* ***Results:*** *The time-to-stand (TTS) in elderly participants is significantly longer in the TP strategy than in the AP and NA strategies. For elderly people, the TP strategy results in upper extremity JM lower than during AP and equal as in NA. Similarly, the TP strategy results in significantly lower MF than the AP strategy, and equal MF as in the NA strategy.* ***Conclusion:*** *The TP strategy takes longer than AP and reduces the JM and MF for elderly participants. Moreover, the TP strategy does not yield higher JM and MF than the NA strategy for any participant group. Thus, the biomechanical advantage of the TP strategy for elderly people, are lowered JM and MF in the upper extremity.*

ABBREVIATIONS

AP	Armrest Push-off
BK	Body Kinematics
CoP	Center of Pressure
DoF	Degrees of Freedom
EF	Elderly Female
EM	Elderly Male
GRF	Ground Reaction Forces
ID	Inverse Dynamics
IK	Inverse Kinematics
JM	Joint Moment
MF	Muscle Forces
NA	No Arm Aid
PK	Point Kinematics
SO	Static Optimization
STS	Sit-to-stand
TP	Thigh Push-off
TSM	Thoracoscapular Shoulder Model
TTS	Time-to-Stand
YM	Young Male

I. INTRODUCTION

GLOBALLY, THE FASTEST-GROWING age group consists of people 65 and older [1]. In the Netherlands, the 65-plus age group has increased by 1.2 million over the past 20 years to a total of 3.46 million in 2021. Over the coming 20 years, this number is expected to grow by another 1.3 million [2]. With age, the human body deteriorates, resulting in mobility-related issues as the levels of physical activity, flexibility, endurance, muscle mass, and muscle strength decrease [2][3][4]. Impeded mobility creates obstacles while performing the activities of daily life and negatively impacts the quality of life [5][6].

Estimating when mobility impediments occur is difficult due to redundancies present in the human body, such as a surplus in muscle mass and neural circuits [7]. The biological redundancy yields a physiological reserve to compensate for the deterioration of the human body [8]. However, the term disregards the redundancy in the musculoskeletal architecture, also described as the functional redundancy. The result of functional redundancy is compensation, which indicates the presence of physical decline [9].

People employ compensation strategies due to a lack of neuromuscular capacity or by making unconscious changes to the movement objective by changing the motion pattern or muscle recruitment [9]. Capacity compensation occurs when at any point during a motion, the person has insufficient neuromuscular reserve [9]. Changes to the movement emerge after altering the motion in an attempt to increase stability or to diminish the energy demand, pain, and velocity [10]. On the short-term, compensation strategies positively affect the levels of functioning in the activities of daily life [11]. However, long-term under- or overuse could negatively affect the neuromuscular capacity. Therefore, understanding the relation between physical decline and compensation strategies employed during activities of daily life is important to help clinicians with decisions in the rehabilitation process. [10].

One of the activities of daily life hindered by impeded mobility is the sit-to-stand (STS) motion. The motion is performed an average of 60 times throughout the day [12]. The motion is necessary when getting out of bed, standing up from a seat, and getting out of a car. Without the ability to stand up, a person depends on the help of a caretaker, making the ability to perform the STS motion essential to living independently [13][14].

Due to the importance, the STS motion is a widely studied activity. Compensation strategies for the STS motion found in the literature include: pacing, movements of the trunk or arms, and asymmetric foot placement [6]. A powerful tool to research the effects of reduced neuromuscular capacity is found in musculoskeletal modeling [10]. Through musculoskeletal models, the limitations of measurement and observation studies are overcome and complemented with simulations [10]. Models allow for a controlled environment wherein a single variable, such as decreased strength, is easily isolated to research the effects. As a result, various papers utilize a musculoskeletal model to study the STS motion [15][16][17][18][19][20][21].

The simulations possible with musculoskeletal models allow for the quantification of parameters such as the muscle forces (MF) and joint moments (JM) [19][21] Therefore, models permit the determination of differences in MF and JM between STS strategies and across age/gender groups [21]. However, most studies regarding the STS motion, focus on the lower extremity, omitting the compensation strategies that occur through movements of the upper body and especially the arms.

Three possible strategies for the STS motion include: thigh push-off (TP), armrest push-off (AP), and no arm aid (NA) [10][19]. The inclusion of arm movements in the TP and AP strategies seem to indicate compensation for age-related decline, yet for what aspect of deterioration is not understood [10]. As most research focuses on the lower limb during the STS motion, analyses on the upper extremity is limited [21]. Furthermore, current studies include data purely on elderly males (EM) and the JM of the upper extremity for the three strategies [19]. Another study focuses on a full body comparison between the AP and NA strategies for three age groups of males [21]. Thus, at the moment data on the MF experienced during the TP strategy is unavailable. Similarly, there is no data on elderly females (EF) for each of the three strategies and the corresponding JM and MF.

Regardless of the limited amount of research considering the biomechanics of the TP strategy, elderly people frequently employ the technique to perform the STS motion [22]. One previous study researched the STS motion in EM and found a reduction in lumbar JM when comparing the TP and NA strategies as well as a reduction in elbow and shoulder JM when comparing the TP and AP strategies [19]. However, the study simplified the shoulder girdle to include purely the glenohumeral joint. Thus, the biomechanical advantage of the TP strategy with respect to the sternoclavicular and scapulothoracic joints as well as the MF remains unknown.

Therefore, this study examines the STS motion in EM, EF, and young males (YM) and determines the JM and MF exerted on the upper extremity during the TP, AP and NA strategies. This will be done by quantifying the JM and MF generated by the groups during each of the three strategies. The research also expands on the current knowledge by checking whether age or gender influences the JM and MF in the TP, AP, and NA strategies. The results found in this study aim to reveal the biomechanical advantage of the TP strategy over the AP and NA strategies for the upper extremity. The information can help clinicians, such as physical therapists, in providing recommendations on STS strategies and with the rehabilitative process.

II. METHOD

A. Participants

Data was adopted from a previous study where the STS motion was recorded for fifty participants [19]. Each participant gave written informed consent to partake in the study, and ethics approval was given by the institutional ethics committee [19]. The participants are categorized into one of four groups: EM, EF, YM, and young females. TABLE 1 shows the averages and a standard deviation of the ages, heights, and weights of the participants along with the size of each of the groups.

The STS motion was evaluated with three different strategies for the arm: TP, AP and NA. During the TP and AP strategies, the participant used their arms to perform the STS motion. In the TP strategy, the participants exerted force with their hands by pushing on their thighs. During the AP strategy the participants placed their hands on the armrests and pushed on those instead. In the NA strategy no force was applied with the hands and the arms were left to the side of the body, or kept in a single position.

TABLE 1
Averages and Standard Deviations of the Age, Weight, and Height for Each Participant Group

Group	n	Age	Weight (kg)	Height (m)
EM	11	76.8 ± 7.19	77.44 ± 13.41	1.74 ± 0.08
EF	12	75.0 ± 5.56	65.98 ± 12.45	1.59 ± 0.11
YM	13	27.3 ± 4.31	77.62 ± 11.64	1.82 ± 0.09
YF	14	27.1 ± 5.05	64.01 ± 8.85	1.69 ± 0.07

During the experiments, every participant performed each strategy three times. To capture the motion 84 markers, were placed on specific landmarks of the body. A 10-camera motion capture system with 100 Hz sampling frequency from Vicon Motion Systems, recorded each of the trials performed. The external forces were measured using force plates from Kistler Holding AG and were placed on the floor, seat, and armrests. The plates provided the force measured at the respective location for each of the three strategies. In the TP trials the force exerted with the hands is not measurable using the force plates. Instead, to measure the force exerted onto the thigh during the TP strategy, a single load disc cell was taped onto the hand. The load cell translated the applied force into an electrical signal, which was interpreted using a raspberry pi [19]. The result provided the force a participant exerted on his thigh, which is further referred to as force glove data. Respectively, the sampling frequencies were 1000 Hz for the plates and 100 Hz for the gloves.

For this thesis the young female participants were excluded. The reason therefore lies in the fact that the EM group forms the standard to which the other groups are compared. The EM group is taken as the basis, due to previous research often including the EM group [19][21]. By looking at the other groups evaluated, the EF group provides information regarding the effect of gender, whereas the YM group on the effect of age. The young female group compares over both factors, and thus provides no additional information to answer the question.

B. Model

The STS motion data obtained, functioned as the input to a 3D musculoskeletal OpenSim model [24]. The model used, is shown in Fig. 1 and combines two already available models: the Rajagopal full-body model and the Thoracoscapular Shoulder model (TSM) [25][26]. Looking at Fig. 1, the global coordinate system defines the positive x-axis as forward motion, y-axis as upward, and z-axis as movement to the left, respectively shown using red, green, and blue colors. The combined model took the lower extremities and the pelvis from the Rajagopal model, and the upper body from the TSM model.

The resulting combined model is single sided and contains a total of 20 rigid bodies. 13 bodies form the lower extremities and 7 bodies create the torso and right arm. The models contains no skull and left arm. The origin of the torso was lowered from the sternum to the fifth lumbar vertebrae. The translation moved the origin -0.0215m in the x and -0.38m in the y direction. The translation was a necessary consequence of differences in the vtp files that describe the geometry of the bones of the torso. All objects dependent on the torso, which includes the bodies and joints of the upper extremity as well as the corresponding muscle attachments and markers, utilized the same translations.

In total the model contained 30 degrees of freedom (DoF): 6 at the pelvis, 5 in each leg, 3 for the torso, 2 for the clavicle, 4 for the scapula, and 5 for the arm. The pelvis, being the first placed body, contains 6 DoF representing rotation and translation. The 3 translative DoF at the pelvis allow the model to make 3D movements away from the starting position. The scapula has 4 DoF, named scapula winging, upward rotation, abduction, and elevation. The scapulothoracic joint is described with using a custom joint where instead of rotation around a point, the scapula glides over an ellipsoid placed on the ribcage [26]. The local coordinate system of the scapula and the aforementioned ellipsoid are shown in Fig. 1. Scapula winging and upward rotation are respectively defined as rotations around the local x and y axis of the scapula. Scapula abduction rotates along the ellipsoid in the local xz-plane and scapula elevation rotates along the ellipsoid in the local yz-plane.

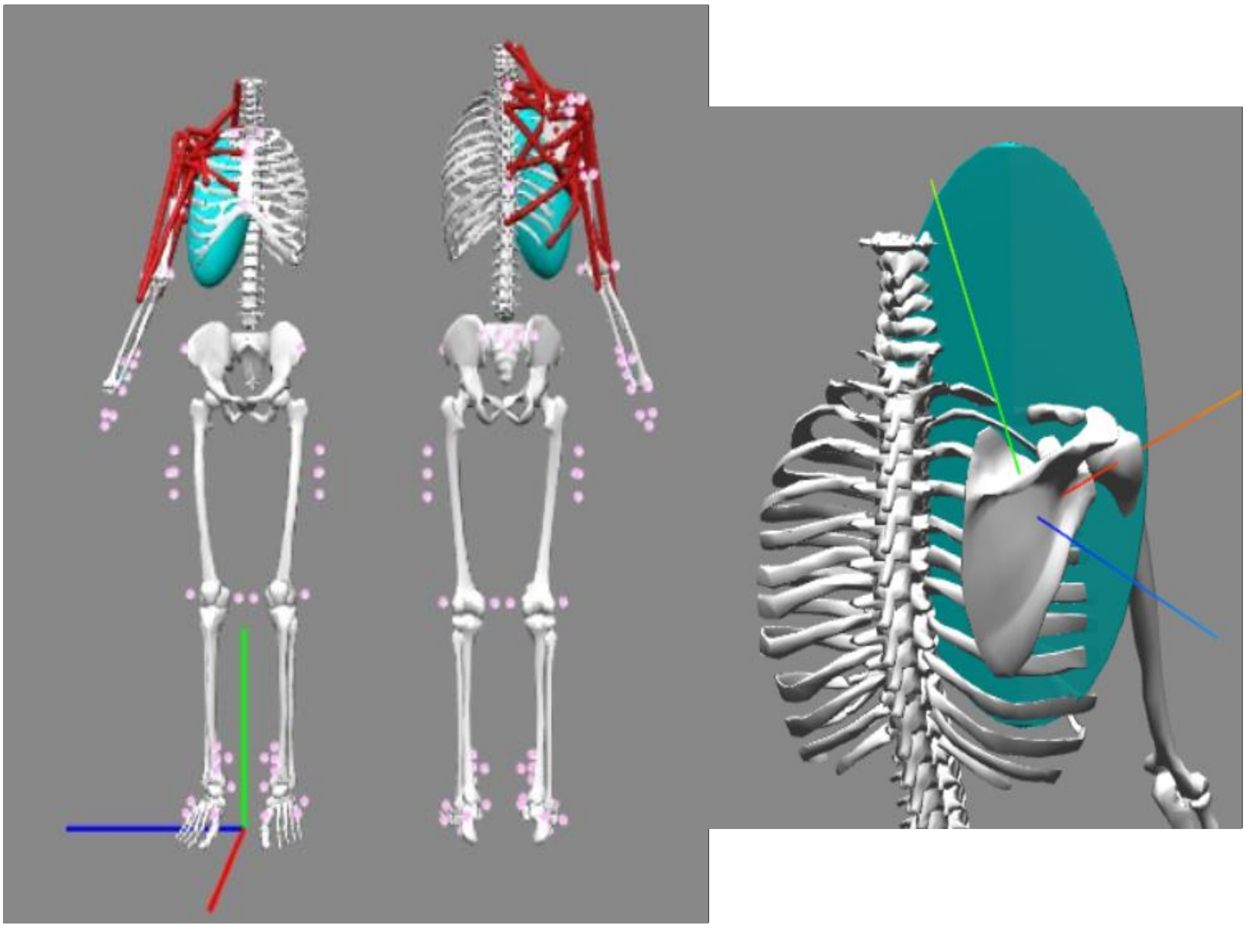


Fig. 1 A: Front (left) and Rear (right) View of the Musculoskeletal Model. The Pink Dots Represent Model Markers. The Coordinate System Shows the X-axis in Red, Y-axis in Green and Z-axis in Blue. B: Close-up of the Scapula with its Local Coordinate System and the Ellipsoid.

The hip, lumbar, and glenohumeral joints are defined as 3 DoF ball-and-socket joints, and the knee, ankle, elbow, and radioulnar joints as a 1 DoF hinge joint. The sternoclavicular joint is limited to 2 DoF to represent protraction and elevation. The model omits axial rotation of the clavicle as it was unmeasurable through palpation and moves marginally. Moreover, simulations revealed that the omission only affects clavicular axial rotation and remains close to the calculated optimal rotation axis [27][28].

The model is actuated by 33 Hill type muscle-tendon actuators and 16 torque actuators. The muscle parameters are adapted from the research of Klein-Breteler and the aggravated bundles are taken from van der Helm et al. [29][28]. The naming scheme of the muscles consists of the muscle's name, on what rigid body it attaches and a letter representing the location of the origin. Only muscles which attach on multiple bodies contain the respective body in the naming scheme. The letters used include middle (M), superior (S), inferior (I), posterior (P), and anterior (A). As an example, the muscle actuator TrapeziusScapulaS represents the trapezius muscle, attaches on the scapula, and the origin lies superior to where it attaches.

The combined model includes purely the muscles from the TSM model. The muscles present in the Rajagopal model were replaced by torque actuators located at each joint in the lower limbs and torso. The replacement of lower leg muscles was done to reduce the simulation time as the focus lied on the MF generated by the upper arm. Therefore, three actuators moved the hip, lumbar, and pelvic joints, and one actuator moved each knee and ankle joint.

C. Time-to-Stand

The time-to-stand (TTS) is defined as the time it takes a participant to perform the STS motion. However, not every participant starts at the same time. Therefore, a metric is required that represents the initialization of the STS motion. The initialization was defined as the moment a participant starts moving their torso forward with a velocity of over 0.2m/s. The motion ends when the person is standing upright, defined by a hip flexion angle of below 3 degrees. Next, the movement is split into two phases, similar to the study by Smith [21]. The first phase runs from the initialization to the moment the participant no longer touches the seat. The exact moment the participant is no longer touching the seat is defined as the first instance that the force plate placed on the seat measures zero. The second phase starts immediately after the first phase and ends when the person stands upright.

D. Scaling

The model was scaled for each participant using a setup file that corresponded to the specific person. Inputs to the setup file included: the static trajectory, scale setup, a participant's bodyweight, and the marker set. The static motion correlates to a recording where the participant stood upright with their palms facing forward. The static trajectory takes the timeframe where the fewest markers are missing and adds the 9 following timeframes. The static trajectory provides the location of each measured marker, which is compared to the location of the model markers to create scaling factors.

The scale factors are determined by comparing the difference in distances between two or more measured and model markers. The scale setup denotes which markers are used to formulate the scaling factors. To adjust the bodyweight for the omission of the skull and left arm, first the total mass of the model was determined. The mass of the left arm coincided with the mass of the right arm. The mass of the skull was determined by comparing the segmental mass of the torso with and without skull [30].

Afterwards, the bodyweight of the participants was adjusted to accommodate for the omission of the skull and left arm. The marker set was brought down from 84 to 65 markers due to the exclusion of markers on the left arm, see

APPENDIX A for the complete list. The scaling process resulted in participant specific models, with the body segments scaled and the markers adjusted. The optimal fiber length, tendon slack length, and muscle attachment locations were also altered in the scaling process. The pennation angle and maximum isometric force remained unchanged by the scaling process.

E. Inverse Kinematics

Inverse Kinematic (IK) simulations were performed with locked subtalar and metatarsophalangeal joints. For each participant, the scaled model, marker trajectory data (TRC) for each trial, and a set of weights placed on the markers (all weighted 1), functioned as the input for the inverse kinematics. At each timeframe, IK uses the formula: $min_q [\sum_{i=marker} w_i |x_i^{exp} - x_i(q)|^2 + \sum_{j=coord} w_j \left(q_j - q\right)^2]$.

The formula calculates the generalized coordinates to fit the trajectory data as close as possible. The formula solves a weighted least squares problem where $w_{i,j}$ are the task weights, x_i^{exp} $x_i(q)$ represent experimental and model markers, and q_j, q the coordinates. Here all marker tasks are weighted equally at 1, whereas all coordinate tasks are 0, reducing the formula to: $min_q [\sum_{i=marker} w_i \left|x_i^{exp} - x_i(q)\right|^2]$. The outputs of IK are the angles of all coordinates at every timeframe of the STS motion.

After running IK, the point kinematics (PK) and body kinematics (BK) were also ran. The PK simulations result in the positions, velocities, and accelerations of the joint centers, whereas the BK simulations result in the positions, velocities, and accelerations of the mass centers of each body. The results of the PK simulations provided the joint centers of the hip and knee. These were later used to split the seat force into two components on each thigh, explained further in section Inverse *Dynamics*. The results of the BK simulations provided the information necessary to determine when the STS motion was initiated through the velocity of the torso. APPENDIX B shows the IK results of one participant for the coordinates of the upper extremity.

F. Inverse Dynamics

The inverse dynamics (ID) determines the forces and torques at each joint required to perform the movement described by a motion file and external forces. The inputs required to perform ID include the motion as obtained through IK and the external loads. The ID simulation output gives the moment measured at every DoF of the at each timeframe. Next the coordinate moments are combined into the JM trough the Pythagorean theory. The coordinate values specified in the IK motion file, are filtered using a low pass filter of 4.7Hz to eliminate noise [31]. The filtering is required as the ID tool amplifies all noise present in the IK motion file. The value of 4.7Hz is in accordance with the predecessors of this thesis as well as several other models [19][32].

The external loads consist of names for the external forces and where on the body the force applies. The loads are described using a motion (.mot) file which contains data on the components of force, torque, and point of application for each frame of the motion. The data implemented into the external load file corresponds to the data measured using the force plates and force gloves. Finally, the force data file is filtered with a low pass filter of 10 Hz, again in accordance with Prinold et. al. [32].

The external forces present in all three strategies are the ground and seat plate forces. Both TP and AP require an additional external force to represent the forces exerted with the hand. All forces, except the hand force during the TP strategy, were expressed in the global frame. The TP hand force was placed in the local frame of the hand. The force on the seat was split into two forces acting on the thighs using the joint centers of the hip and knee, obtained from the PK simulations. The first step is to create a normalized direction vector which represents the longitudinal axis of the thigh. The formula creating this vector is described by $dir = \frac{K_{jc}-H_{jc}}{norm(K_{jc}-H_{jc})}$, where, K_{jc} & H_{jc} represent the knee and hip joint center. Next the seat force is placed on the direction vector using the formula: $z_{val} = \frac{CoP_{seatX}-H_{jcX}}{dir_X} \cdot dir_z + H_{jcZ}$. In the formula, the subscripts (x,z) denote what component of the 3D point is taken, CoP represents the seat center of pressure, dir_x the direction vector, and H_{jc} the hip joint center. All values in both formulas are expressed in meters and relative to the ground frame.

G. Static Optimization

The static optimization (SO) simulations were performed after running the ID. The inputs for the ID simulations are reused to perform the simulation. The cost function implemented by OpenSim minimizes the activations of the muscles and actuators. Additionally static optimization requires a set of reserve and residual actuators. Each DoF actuated by muscles is appended with a reserve actuator. There are six residual actuators are placed on the first placed body of the model, which is the pelvis, to represent three translative and rotative forces.

The outputs are the forces and activations of each muscle and torque actuator. The muscle forces were filtered using a low pass filter of 4.7Hz. The resulting muscle forces were compared to the results of simulations performed by Seth et al, to check if the values were in the same order of magnitude [26]. The movements performed in the study of Seth et al. include: humeral flexion or abduction and shrugging [26]. Another check was made to see whether the forces were generated by the muscles rather than the reserve actuators. The joint torque is primarily generated by the muscles, if the activations and force generated by the reserve actuators is sufficiently low (<0.1).

H. Statistics

To check if the TTS, hand force, JM, and MF contained significant differences, statistical tests were ran. Prior to the statistical tests, the averages and standard deviations were calculated per participant for each of the three strategies. Next, the results were averaged for each of the participant groups, which coincided as the inputs to the statistical tests, meaning an ANOVA test was in order. However, prior to running an ANOVA comparison, the data needs to be checked for normality. To test for normality, the Shapiro Wilk's test ($p > 0.05$) was executed on the results. As all data was normally distributed, the results of the simulations were checked for significant differences using a two way mixed ANOVA.

The ANOVA comparison uses the three STS strategies and participant groups as factors to check for differences between the participant groups and strategies. Matlab was used to perform both the Shapiro Wilk's test and the ANOVA tests. Statistical significance was assumed if p-values were smaller than 0.05.

III. RESULTS

A. Participants

Due to issues with the marker data, two YM participants could not be scaled and had to be excluded from the simulations. The data on the remaining 34 participants, 11 EM, 12 EF, and 11 YM, was used to perform the IK simulations. The participants performed each strategy three times, enabling a total of 102 IK simulations. However, for all three strategies at least one trial lacked the corresponding trajectory data. In TP all three trials of a YM missed, reducing the total to 33 participants. In AP one trial of an EF participant missed. Lastly, in NA five trials of EF participants missed, one EF missed a single trial and two EF missed two trials.

Another exclusion criterion was lacking data regarding the external forces. Due to the model only including the right arm, especially TP simulations were affected as data for the right force glove often missed. For 13 participants; 3 EM, 4 EF, and 6 YM, the force glove data missed for all TP trials. Furthermore, 4 participants (2 EM, 1 EF, and 1 YM) lacked the corresponding hand force for either 1 or 2 trials (one EM), totaling 5 trials. These exclusions decreased the size of the participant groups to: 8 EM, 8 EF, and 4 YM. Moreover, the number of TP simulations possible lowers from 99 during IK to 55 for both ID and SO.

The ID and SO simulations share the same inputs and are dependent on the IK motion. Therefore, if no IK motion data is available, the corresponding ID and SO simulations are excluded. As a result, the number of performed ID and SO simulations is equal. However, in the AP strategy, three trials from an EF were excluded during the ID and SO simulations. The results of these simulations were erroneous, as the armrest force plates continuously measured a non-zero force. No further exclusions were necessary for the AP strategy, lowering the total number of simulations to 94. Lastly, the NA strategy contained no exclusions for the ID/SO trials.

TABLE 2
Number of Participants and Trials per Strategy.

	IK		ID/SO	
	Participants	**Trials**	**Participants**	**Trials**
TP	33	99	20	55
AP	34	101	33	94
NA	34	97	34	97

B. Time-to-Stand

TABLE 3 shows the durations of the two phases and the total TTS. In each strategy, there is no statistical difference in the duration of phase 1. In phase 2 and the total TTS the same statistical significant differences appear. Comparing the different strategies shows that for both EM and EF, the TP strategy takes significantly longer than the AP and NA strategies. For the YM group there are no significant differences between the three strategies. Looking at the disparities between the EM and EF groups, there are no statistically significant differences between the EM and YM groups. The durations of phase 2 and the total TTS are significantly shorter for the YM group.

TABLE 3
Average and Standard Deviation of the Duration of the Phases of the Different STS Strategies in Seconds .

Phase	**Strategy**	**EM**	**EF**	**YM**
1	TP	0.25 ± 0.09	0.3 ± 0.06	0.21 ± 0.03
	AP	0.23 ± 0.06	0.29 ± 0.08	0.21 ± 0.05
	NA	0.21 ± 0.05	0.29 ± 0.07	0.2 ± 0.03
2	TP	1.45 ± 0.53	1.34 ± 0.40	**0.98 ± 0.12** [c]
	AP	**0.97 ± 0.12** [a]	**0.98 ± 0.13** [a]	0.89 ± 0.19
	NA	**1.00 ± 0.17** [b]	**0.98 ± 0.17** [b]	0.88 ± 0.22
Total	TP	1.70 ± 0.58	1.64 ± 0.52	**1.19 ± 0.12** [c]
	AP	**1.20 ± 0.15** [a]	**1.26 ± 0.14** [a]	1.1 ± 0.15
	NA	**1.21 ± 0.19** [b]	**1.27 ± 0.18** [b]	1.08 ± 0.2

a <0,05: Significant difference between the TP and AP strategy per group
b <0,05: Significant difference between the TP and NA strategy per group
c <0,05: Significant difference between EM-EF, and EM-YM per strategy

C. Hand Force: Glove and Plate

The force exerted on the thighs and armrests is represented by the force glove and armrest force plate data. The force on the armrest plate is combined. As the model is single sided, only data regarding the right hand is incorporated. Therefore, TABLE 4 shows the averaged peak hand force for each participant group during the TP and AP strategies corrected for the body weight, expressed in N/BW(kg*9.81). During the TP strategy, EM and EF exert significantly less force with their hands than in the AP strategy. Comparing across the participant groups the EM exert significantly more force than the YM during the AP strategy.

TABLE 4
Averaged peak force exerted with the right hand. Forces are shown in N/BW

Eternal Force	Strategy	EM	EF	YM
Right Hand	TP	0.09 ± 0.04	0.07 ± 0.02	0.06 ± 0.06
	AP	**0.2 ± 0.06** [a]	**0.12 ± 0.08** [a]	**0.15 ± 0.12** [b]
	NA	[ ]	[ ]	[ ]

a <0,05: Significant difference between the TP and AP strategy per group
b <0,05: Significant difference between EM-YM per strategy

D. Inverse Dynamics

The ID simulations calculate the generalized moments around each DoF of the model. The moments around each coordinate were combined to obtain the moment around the joint. TABLE shows the averaged peak JM of all strategies for each participant group corrected for the body weight expressed in newtons. Peak moments on the sternoclavicular joint are negligible (<0.003 Nm/kg) for each of the three strategies and therefore not included in TABLE 5.

Comparing the TP to the AP strategy shows that both the EM and EF participants experience significantly lower peak JM during the TP strategy for the scapulothoracic, glenohumeral, elbow, and radioulnar joints. Comparing the AP and NA strategies shows the same significant differences as between TP and AP. Moreover, the YM participants experience significantly lower JM in purely the radioulnar joint during the TP strategy. Comparing the TP and NA strategies shows there are no significant differences in peak JM for all participant groups and all joints.

When comparing the EM and EF, the elbow and radioulnar joints presented a statistical significance in the AP strategy. In both joints the peak JM of the EM is higher than the JM of the EF. Between the EM and YM groups the peak JM achieved during AP is significantly lower in each joint for the YM group. The TP and NA strategies show no statistical differences between the groups.

TABLE 5
Averaged peak joint moments for each participant group corrected by the body weight. Moments are shown in Nm\kg

Joint	Strategy	EM	EF	YM
Scapulothoracic	TP	0.24±0.04	0.21±0.05	0.25±0.03
	AP	**0.90±0.30** [a]	**0.63±0.3** [a]	**0.82±0.47** [c]
	NA	**0.33±0.09** [b]	**0.25±0.09** [b]	0.25±0.05
Glenohumeral	TP	0.18±0.02	0.15±0.03	0.19±0.04
	AP	**0.66±0.24** [a]	**0.41±0.24** [a]	**0.6±0.39** [c]
	NA	**0.19±0.06** [b]	**0.14±0.07** [b]	0.14±0.02
Elbow	TP	0.05±0.02	0.04±0.01	0.06±0.01
	AP	**0.52±0.21** [a]	**0.19±0.12** [a, c]	**0.34±0.24** [c]
	NA	**0.07±0.02** [b]	**0.05±0.02** [b]	0.05±0.01
Radioulnar	TP	0±0	0±0	0±0
	AP	**0.25±0.11** [a]	**0.11±0.13** [a, c]	**0.2±0.21** [a, c]
	NA	**0.01±0** [b]	**0±0** [b]	**0±0** [b]

a <0,05: Significant difference between the TP and AP strategy per group
b <0,05: Significant difference between the AP and NA strategy per group
c <0,05: Significant difference between EM-EF, and EM-YM per strategy

E. Static Optimization

The force generated by the reserve actuators was sufficiently low yielding values lower than 0.1N. Thus, the forces calculated in the SO simulations are primarily generated by the muscle actuators. TABLE 4shows the average peak MF generated by each participant group during the three strategies. The values shown in TABLE 4are corrected for body weight and expressed in N/BW(kg*9.81). Only the muscles that contain a statistically significant difference are shown in TABLE 4, and the complete table is added in APPENDIX D.

Some of the muscle fascicles contributed minimally to every strategy in all participant groups resulting in a peak MF of below 0.05N/BW. The muscles include the Trapezius Scapula M & S, Serratus Anterior I & S, Rhomboideus S & I, Latissimus Dorsi S, M & I , and Pectoralis Minor. Comparing the peak MF of these muscles throughout the strategies and participant groups, gives differences with a negligible magnitude. Irrespective of these small differences in MF some contain statistical significance. The EM and EF produce significantly more force during the AP than the TP and NA strategies with all heads of the Latissimus Dorsi and the Pectoralis Minor muscles. Moreover, EM also generate significantly more force during AP than TP and NA with the Rhomboideus I muscle.

All muscles included in TABLE 4, show that for at least one of the three participant groups the peak MF achieved during the AP strategy is significantly higher than during the TP and/or the NA strategy. In the remainder of this paragraph the AP strategy results in higher MF than both the TP and NA strategies unless a muscle of participant group is followed by a bracketed statement. All groups experience significantly higher MF in the Deltoideus Scapula M and Teres Major muscles. The same occurs for both EM and EF in the Levator Scapulae (only NA), Pectoralis Major Torso I, Infraspinatus S and Subscapularis S, M & I muscles. The EM group in the Trapezius Clavicle S (only TP), Serratus Anterior M, Coracobrachialis, and Supraspinatus P & A muscles. Lastly, for both the EF (only TP) and YM group in the Biceps Short Head muscle, and for the YM in the Deltoideus Clavicle A (only TP) muscle.

TABLE 4Comparing the differences between the TP and NA strategies shows that the NA strategy generates significantly lower peak MF. The EM exert significantly less force with the Pectoralis Major S & M muscles, the EF and YM groups with the Deltoideus Clavicle A muscle.

Lastly, there are some statistically significant differences between the participant groups. Both the EF and YM generate significantly lower peak MF during the AP than the EM using the Coracobrachialis and Pectoralis Major Torso M muscles. Furthermore, the peak MF of the Pectoralis Major Torso I muscle is significantly lower during the AP strategy of YM than of EM.

TABLE 4

Averaged Peak Muscle Forces for each Participant Group. Forces are shown in N/BW

a <0,05: Significant difference between the TP and AP strategy per group

b <0,05: Significant difference between the TP and NA strategy per group

c <0,05: Significant difference between the AP and NA strategy per group

d <0,05: Significant difference between EM-EF, and EM-YM per strategy

Muscle	Strategy	EM	EF	YM
Trapezius Clavicle S	TP	0.06 ± 0.01	0.05 ± 0.03	0.07 ± 0.01
	AP	**0.11 ± 0.03** [a]	0.08 ± 0.03	0.12 ± 0.04
	NA	0.07 ± 0.03	0.05 ± 0.02	**0.08 ± 0.02** [c]
Serratus Anterior M	TP	0.14 ± 0.03	0.14 ± 0.05	0.15 ± 0.09
	AP	**0.19 ± 0.08** [a]	0.14 ± 0.07	0.18 ± 0.16
	NA	**0.10 ± 0.02** [c]	0.1 ± 0.01	0.07 ± 0.02
Rhomboideus I	TP	0.01 ± 0	0.02 ± 0.01	0.01 ± 0
	AP	**0.03 ± 0.03** [a]	0.04 ± 0.02	0.01 ± 0.01
	NA	**0.01 ± 0** [c]	0.02 ± 0.01	0.01 ± 0.01
Levator Scapulae	TP	0.09 ± 0.03	0.07 ± 0.02	0.07 ± 0.05
	AP	0.08 ± 0.05	0.09 ± 0.03	0.06 ± 0.02
	NA	**0.05 ± 0.01** [c]	**0.06 ± 0.01** [c]	0.05 ± 0.02
Coracobrachialis	TP	0.09 ± 0.05	0.1 ± 0.04	0.07 ± 0.05
	AP	**0.28 ± 0.22** [a]	**0.12 ± 0.08** [d]	**0.24 ± 0.32** [d]
	NA	**0.07 ± 0.05** [c]	0.08 ± 0.02	0.05 ± 0.02
Deltoideus Clavicle A	TP	0.45 ± 0.36	0.37 ± 0.22	0.34 ± 0.16
	AP	0.54 ± 0.41	0.26 ± 0.3	**0.47 ± 0.31** [a]
	NA	0.19 ± 0.13	**0.14 ± 0.04** [b]	**0.15 ± 0.06** [b]
Deltoideus Scapula M	TP	0.24 ± 0.05	0.27 ± 0.1	0.19 ± 0.07
	AP	**0.81 ± 0.54** [a]	**0.59 ± 0.26** [a]	**0.66 ± 0.56** [a]
	NA	**0.24 ± 0.07** [c]	**0.21 ± 0.04** [c]	**0.22 ± 0.03** [c]
Latissimus Dorsi S	TP	0 ± 0	0.01 ± 0	0.00 ± 0.00
	AP	**0.01 ± 0.01** [a]	**0.01 ± 0.01** [a]	0.01 ± 0.00
	NA	**0 ± 0** [c]	**0.01 ± 0** [c]	0 ± 0
Latissimus Dorsi M	TP	0.01 ± 0	0.01 ± 0	0 ± 0
	AP	**0.03 ± 0.02** [a]	**0.02 ± 0.02** [a]	0.02 ± 0.02
	NA	**0.01 ± 0** [c]	**0.01 ± 0** [c]	0.01 ± 0
Latissimus Dorsi I	TP	0 ± 0	0.01 ± 0	0 ± 0
	AP	**0.02 ± 0.02** [a]	**0.02 ± 0.01** [a]	0.02 ± 0.05
	NA	**0 ± 0** [c]	**0 ± 0** [c]	0 ± 0
Pectoralis Major Clavicle S	TP	0.22 ± 0.11	0.13 ± 0.05	0.14 ± 0.09
	AP	0.28 ± 0.12	0.12 ± 0.08	0.27 ± 0.19
	NA	**0.09 ± 0.04** [b, c]	0.07 ± 0.02	0.09 ± 0.03
Pectoralis Major Torso I	TP	0.05 ± 0.02	0.05 ± 0.03	0.04 ± 0.06
	AP	**0.25 ± 0.14** [a]	**0.15 ± 0.13** [a]	**0.23 ± 0.26** [d]
	NA	**0.01 ± 0** [c]	**0.02 ± 0.01** [c]	0.01 ± 0
Pectoralis Major Torso M	TP	0.31 ± 0.19	0.18 ± 0.07	0.15 ± 0.22
	AP	0.46 ± 0.16	**0.23 ± 0.19** [d]	**0.3 ± 0.3** [d]
	NA	**0.08 ± 0.05** [b, c]	**0.04 ± 0.03** [c]	**0.06 ± 0.04** [c]
Teres Major	TP	0.2 ± 0.18	0.14 ± 0.11	0.06 ± 0.03
	AP	**0.46 ± 0.31** [a]	**0.35 ± 0.17** [a]	**0.32 ± 0.17** [a]
	NA	**0.08 ± 0.06** [c]	**0.06 ± 0.02** [c]	**0.08 ± 0.03** [c]
Infraspinatus S	TP	0.08 ± 0.04	0.09 ± 0.02	0.06 ± 0.01
	AP	**0.23 ± 0.2** [a]	**0.22 ± 0.14** [a]	0.24 ± 0.34
	NA	**0.08 ± 0.03** [c]	**0.07 ± 0.02** [c]	0.06 ± 0.01
Pectoralis Minor	TP	0.01 ± 0	0.01 ± 0	0.01 ± 0
	AP	**0.03 ± 0.01** [a]	**0.03 ± 0.02** [a]	0.01 ± 0.01
	NA	**0.01 ± 0** [c]	**0.01 ± 0** [c]	0.01 ± 0

Subscapularis S	TP	0.07 ± 0.02	0.06 ± 0.01	0.04 ± 0.01
	AP	**0.15 ± 0.04** [a]	**0.14 ± 0.07** [a]	0.13 ± 0.11
	NA	**0.04 ± 0.01** [c]	**0.04 ± 0.01** [c]	0.03 ± 0.02
Subscapularis M	TP	0.06 ± 0.03	0.04 ± 0.01	0.03 ± 0.01
	AP	**0.13 ± 0.05** [a]	**0.08 ± 0.04** [a]	0.1 ± 0.08
	NA	**0.03 ± 0.01** [c]	**0.03 ± 0.01** [c]	0.03 ± 0.01
Subscapularis I	TP	0.17 ± 0.08	0.11 ± 0.05	0.07 ± 0.03
	AP	**0.33 ± 0.16** [a]	**0.24 ± 0.13** [a]	0.22 ± 0.15
	NA	**0.08 ± 0.03** [c]	**0.07 ± 0.02** [c]	0.07 ± 0.03
Supraspinatus P	TP	0.03 ± 0.01	0.03 ± 0.01	0.02 ± 0.01
	AP	**0.07 ± 0.06** [a]	0.04 ± 0.04	0.08 ± 0.1
	NA	**0.02 ± 0.01** [c]	0.03 ± 0.01	0.02 ± 0.01
Supraspinatus A	TP	0.07 ± 0.02	0.08 ± 0.03	0.05 ± 0.02
	AP	**0.19 ± 0.18** [a]	0.13 ± 0.13	0.14 ± 0.16
	NA	**0.06 ± 0.02** [c]	0.06 ± 0.02	0.05 ± 0.01
Biceps Shorthead	TP	0.06 ± 0.01	0.06 ± 0.02	0.07 ± 0.01
	AP	0.04 ± 0.04	**0.03 ± 0.01** [a]	**0.06 ± 0.06** [a]
	NA	0.06 ± 0.04	0.05 ± 0.03	**0.05 ± 0.02** [c]

IV. DISCUSSION

This study examines the STS motion in EM, EF & YM and determines the JM and MF exerted on the upper extremity during the TP, AP and NA strategies. The results found in this study aim to reveal the biomechanical advantage of the TP strategy over the AP and NA strategies for the upper extremity. This was achieved by quantifying the JM and MF in the upper extremity for the TP, AP, and NA strategies. The results found in this study showed EM and EF experience significantly lower JM and MF in the upper extremity when using the TP strategy instead of the AP strategy. Furthermore, there were no significant differences in JM and MF between the TP and NA strategy for all participant groups. Thus, for all groups and considering the upper extremity, using the TP strategy is advantageous in lowering JM and MF when compared to the AP strategy, and does not result in higher JM and MF than the NA strategy.

Furthermore, this study is the first to quantify the MF of the upper extremity during the TP strategy and in determining the JM present at the scapulothoracic joint. Hence, the values for the JM and MF present at the scapulothoracic joint during the TP strategy, cannot be evaluated against existing literature. Nevertheless, the results of the TTS are comparable to the results of Hendriksen and Smith [19][21]. The results of the peak MF of EM and YM in the AP and NA strategies are in accordance to the results found by Smith [21]. Lastly, the peak JM achieved during the TP strategy for the glenohumeral, elbow, and radioulnar joints are compatible with the arm JM found in the study by Hendriksen [19].

A. Time To Stand

Across the strategies and participant groups the durations of phase 1 were similar, which is in accordance with Hendriksen and Smith [19][21]. Moreover, the results for phase 2 and the TTS are also compatible with the literature. The results found in this and Smith's study show no difference in duration between the AP and NA strategies [21]. Furthermore, the TTS of EF in the TP strategy is significantly longer and no differences appear across all strategies for the YM group.

The EM and EF groups both showed the same results, total TTS for the TP strategy significantly higher than in both the AP and NA strategies. However, no statistically significant differences were found between the EM and EF groups. Thus, sex gives no significant differences for the TTS. For the YM group changing the strategy gives no differences in the TTS. The YM group was significantly faster than the EM group only during the TP strategy, meaning age affects the duration of the TP strategy. The results show that there is compensatory behavior in EM and EF during the TP strategy as the TTS increases, most likely to increase stability.

B. Inverse Kinematics

The resulting motion file obtained through the IK simulations functions as an input for the ID and SO simulations. Since the model used in this study differs from the model used in Hendriksen, a check is needed to determine if the change in model leads to unexpected alterations of the IK results [19]. Any major discrepancies are indicative of an error made in combining the TSM and Rajagopal models, or in scaling the model. To confirm similarity of IK results in both studies, results of each IK simulation were plotted along with the corresponding result found in the study by Hendriksen [19]. The plots contain purely the coordinates of the torso and lower extremities, since these coordinates are equally defined. For visualization, one of the comparisons is added in APPENDIX E. After analysis it became apparent that the motion patterns are compatible, yielding only slight differences. The origin of the difference is found in the weights of the marker tasks provided in the scaling process. As a result the positions of the markers in the scaled model differ, which affects the calculation of the IK simulation.

In both studies, the coordinates representing pelvis list and pelvis rotation both contain an instantaneous change in the angle, approaching a vertical line. The shift is caused by the calculation of the generalized coordinates and missing marker data in the TRC file. When a marker attains a ‘not a number’ (NaN) value at one timeframe, that marker is not used in the calculation of the generalized coordinates. If a one of three markers placed on the right side of a body misses, the calculation only uses the two remaining markers for the right side. When marker placement on left side is tilted away from the neutral position, the solution favors shifting the coordinate angle towards the left because if tilted, the sum of marker errors is smaller. When data on the missing marker is available, the solution finds a more ‘neutral’ position.

C. Hand Force: Glove and Plate

The hand force EM and EF exert during the TP strategy is significantly lower than during the AP strategy. For the YM, there is no difference in force exerted for the strategies. Furthermore, the EM exert significantly more force during the AP strategy than the YM. The differences in force measured during the TP and AP strategies is partially caused by the combination of the individual force components present during the AP strategy. However, taking purely the y-component of the force exerted in AP results in the same statistically significant difference. Thus, irrespective of the x-/z-components, the force EM and EF exert with the hand is higher in AP than in TP.

The origin of the difference is located in the lower body. Hendriksen found greater MF in the lower extremity during the TP strategy than during AP [19]. The results found here show that the decrease in force exerted in the legs during AP is compensated by increasing the hand push-off force. Another reason for the increase in hand force could lie in the positioning of the hand. During the AP strategy, a wider (z direction) center of mass of the hand coincides with lower forces measured with the armrest plate. In the TP strategy the hand's center of mass is always further inward than during AP, explaining the lower force.

D. Inverse Dynamics

Comparing the results of the ID simulations to literature is troublesome as Hendriksen gives the moments present around the DoF of the arm and Smith provides purely glenohumeral joint reaction force [19][21]. Furthermore, joint definitions of the models used in this and Hendriksen's study differ, also complicating comparisons [19]. Purely the model used in this study includes DoF for the scapula and clavicle. Regardless of the described issues, the results found in this study are in agreement with the results found in literature [19][21].

The results found, show that regardless of age or gender, the TP strategy does not generate greater peak JM in any of the upper extremity joints than the NA strategy. Moreover, the peak JM present in all upper extremity joints are significantly lower for both the EM and EF groups during the TP strategy than during AP. For the YM participants the TP strategy significantly lowers the JM present in the radioulnar joint. Moreover, the results indicate EM have significantly higher peak JM in all joints than YM during the AP strategy. The results show presence of compensation in EM, most likely due to the reduction in overall strength as a result of the aging process.

The differences in the values of the JM can be found in either the results of the IK simulations or in the external forces since they function as the inputs to ID. Generally, the JM in the upper extremity increase when the movement pattern is larger, or if the external force applied with the hand is bigger. If during the STS motion the participant uses more arm movements, the motion pattern increases. Both reasons cause the increased JM experienced during the AP strategy compared to TP.

Between TP and NA strategies there are no significant differences, even though higher values for TP were initially expected due to the external hand force present in TP. The reason for lack of differences lies in the motion pattern. During the NA strategy, in some trials the participants kept the elbows flexed, whereas in others the arms were left to the side. The inconsistency in the execution of the NA strategy yields discrepancies in the peak JM. If the elbows were continuously flexed, the JM in the elbow and radioulnar joints decreased, at the cost of more movement in the upper arm and higher peak JM in the glenohumeral and scapulothoracic joints.

Contrarily, the TP movement was performed consistently and with smaller or equal motion patterns as the NA strategy. The motion pattern is deemed equal whenever the elbow was not continuously flexed throughout the STS motion. As a consequence, the results of the scapulothoracic and glenohumeral JM for individual participants were higher in NA than TP if the elbow remained flexed, and all JM were lower if the motion pattern was equal. The latter is attributable to the additional external hand force whereas the former is due to the increase of humeral motion.

Irrespective of gender and age, the TP strategy does not yield larger peak JM on the upper extremity than NA. The TP strategy also generates significantly lower peak JM than AP in all groups. Therefore, when considering purely the upper extremity, TP becomes the advisable strategy over AP if the NA strategy is not viable. Including the JM present in the entire body shows a trade-off between the joints of the upper extremity, lower extremity, and lumbar joint [19]. TP reduces JM in the upper extremity and lumbar joint, AP in the lower extremity and lumbar joint, and NA unloads the upper extremity [19]. The most beneficial strategy is either the TP or AP strategy depending on what joints should be unburdened, TP for upper extremity, AP for lower extremity. The NA strategy yields no benefit over the TP and AP strategies in terms of lowering the peak JM in both the upper and lower extremity.

E. Static Optimization

Only the MF exerted during the AP strategy can be compared to the results found in the study by Smith [21]. In both studies the MF generated by EM is higher than the MF of YM. Furthermore, both studies find the same muscles providing the biggest contribution to the MF required to perform the AP strategy. The muscles include the scapular part of the Trapezius, Serratus Anterior, Pectoralis Major, Deltoideus, Teres Major, Supraspinatus, and the Triceps. Similarly, both studies find the same muscles having negligible contributions, including the Rhomboideus, Latissimus Dorsi, and Pectoralis Minor. The concurrence in influential and inconsequential muscles signifies consistency in both studies. The studies show the same muscle groups impacting the AP strategy, regardless of age, meaning these muscles should be considered to improve performance of the AP strategy.

Although both studies show consistent results for the EM and YM groups during the AP strategy, the values for the peak MF vary. Two reasons cause the inequalities, the participants and the models differed between both studies. Each participant has a different physiology in terms of length, weight, and muscle strength. The physiological aspects affect body sizes and the locations of muscle attachments present in the model. Between the models, definitions for the muscles differ. The model used in Smith's study contains more fascicles to represent a single muscle, resulting in different muscle attachments and pathways. Lastly the MF of individual fascicles is combined into a single value, further affecting the gap in MF [21]. The differences affect the conclusions regarding individual muscle contributions, whereas the general trend of most and least influential muscles remains consistent.

The MF found for the TP and NA strategy share the pattern of most and least influential muscles. Their results further support the conclusion to which muscles of the upper extremity are most influential for the STS motion. Furthermore, the results also show that the TP strategy generates significantly less force than the AP strategy, consistent with the results of the peak JM. Additionally, the TP strategy results in significantly higher MF for purely the Deltoideus Clavicle A and Pectoralis Major Clavicle S muscles. Therefore, the NA strategy also yields no benefit over the TP in lowering MF of the upper extremity. As the SO simulations uses the same inputs as the ID simulations, the reason for the lack of differences is located in the variations of the motion pattern of the NA movement.

Lastly, for the Coracobrachialis and the Pectoralis Major Torso M & S muscles, EM exert significantly more MF during the AP strategy than the EF and YM groups. The results herein show compensatory behavior from the EM, most likely due to a decrease of strength in the lower extremity. The results of the MF lead to a similar conclusion as for the JM. The NA strategy holds no benefit in terms of reducing the MF of the upper extremity in TP as well as lower extremity in both TP and AP [19]. The TP strategy results in significantly lower upper extremity MF than in the AP strategy, and in higher MF for the lower extremity [19]. Thus, the most beneficial strategy is either the TP or AP strategy depending on the where a participant is weaker. A person with shoulder injury, should employ the TP or NA strategy, and a person with an ankle injury, the AP strategy.

F. Limitations

The model used to represent the upper extremity was validated for several motions. The motions simulated by Seth et al. included abduction, shrugging and arm flexion. The STS motion in both TP and AP requires notably more movement of the humerus and scapula than in the motions Seth et al. simulated [26]. Therefore, the shoulder model is not validated for the STS motion specifically. However, between both studies, there are no notable differences in order of magnitude of the MF reached. Therefore, it is likely that the model used in this study, can be used in future research regarding the arm during the STS motion.

The marker placement is also a limiting factor. The difference in torso origin present in the geometry (vtp) files of the Rajagopal and TSM torso, leads to an uncertainty in the placement of markers present on the torso. The translation of torso origin was determined by hand and fits closely, yet uncertainty always arises with such processes. Similarly, marker placement on the scapula and thorax was performed through careful examination of the markers present in both models. Through the custom nature of the scapulothoracic joint in the TSM model, comparisons to the scapula in the Rajagopal model are burdensome. Consequently, there are possible errors in virtual marker placement on the scapula.

Lastly, the force plate data collected during the TP experiments posed a limitation for this study, as it lead to exclusion of 13 participants. The decrease in sample size could result in less accurate values for the averages. The results found in this study do not seem to be affected by the small sample size, as most values fall inside the 95% confidence interval.

G. Recommendations

It is recommended to develop a model which includes the left arm as well as a realistic representation of the spine. The addition of the left arm enables researchers to check whether there are biomechanical differences between the dominant and nondominant arms of a person. Addition of a realistic spine complements this research by showing which strategy is least demanding for the back. By modeling the spine to represent the individual vertebrae, it becomes possible to determine the load of the STS motion at specific locations. The understanding of the loads experienced at each vertebrae is usable in advising people which back problems such as herniated discs.

V. CONCLUSIONS

- The TTS in the TP strategy is significantly longer than in AP and NA, for both the EM and EF groups. There are no differences in the TTS of all three strategies for the YM group. Thus, the TP strategy only takes longer for elderly people.
- The force EM and EF exert with the hand is significantly lower during the TP strategy than during AP. Furthermore, EM exert significantly more force than YM during the AP strategy, which shows compensation by the EM participants.
- The sternoclavicular JM are negligible for all participant groups and each strategy of the STS motion.
- For all participant groups, the peak JM reached during the TP strategy is significantly lower than the peak JM achieved during the AP strategy.
- Regardless of age or sex, the TP strategy does not generate greater peak JM than the NA strategy.
- The EM have higher peak JM than the YM during the AP strategy, indicative of compensation by the EM participants.
- For all participant groups the TP strategy results in significantly lower peak MF than the AP strategy. .
- The TP strategy does not generate significantly more MF than the NA strategy for all participant groups.
- To improve performance of the STS motion, focus on the muscles with the greatest contribution to the STS motion. These muscles are the Trapezius, Serratus Anterior, Deltoideus, Pectoralis Major, Teres Major, Infraspinatus, Subscapularis, Supraspinatus, Triceps, and Biceps.
- The advisable strategy depends on where a participant is weaker. The TP strategy to reduce JM and MF in the upper extremity and lower back, and the AP strategy for the lower extremity and lower back.

REFERENCES

[1] U. Nations, “Ageing.” 2019. [Online]. Available: https://www.un.org/en/global-issues/ageing

[2] M. Visser *et al.*, “Muscle Mass, Muscle Strength, and Muscle Fat Infiltration as Predictors of Incident Mobility Limitations in Well-Functioning Older Persons,” 2005. [Online]. Available: https://academic.oup.com/biomedgerontology/article/60/3/324/630583

[3] Z. Milanović, S. Pantelić, N. Trajković, G. Sporiš, R. Kostić, and N. James, “Age-related decrease in physical activity and functional fitness among elderly men and women,” *Clin Interv Aging*, vol. 8, pp. 549–556, 2013, doi: 10.2147/CIA.S44112.

[4] A. Trombetti *et al.*, “Age-associated declines in muscle mass, strength, power, and physical performance: impact on fear of falling and quality of life,” *Osteoporosis International*, vol. 27, no. 2, pp. 463–471, Feb. 2016, doi: 10.1007/s00198-015-3236-5.

[5] J. C. Davis *et al.*, “Mobility Is a Key Predictor of Change in Well-Being among Older Adults Who Experience Falls: Evidence from the Vancouver Falls Prevention Clinic Cohort,” *Arch Phys Med Rehabil*, vol. 96, no. 9, pp. 1634–1640, Sep. 2015, doi: 10.1016/j.apmr.2015.02.033.

[6] S. Musich, S. S. Wang, J. Ruiz, K. Hawkins, and E. Wicker, “The impact of mobility limitations on health outcomes among older adults,” *Geriatr Nurs (Minneap)*, vol. 39, no. 2, pp. 162–169, Mar. 2018, doi: 10.1016/j.gerinurse.2017.08.002.

[7] L. A. Lipsitz, “Dynamics of Stability: The Physiologic Basis of Functional Health and Frailty,” 2002. [Online]. Available: https://academic.oup.com/biomedgerontology/article/57/3/B115/550371

[8] A. Clegg, J. Young, S. Iliffe, M. O. Rikkert, and K. Rockwood, “Frailty in elderly people,” in *The Lancet*, 2013, vol. 381, no. 9868, pp. 752–762. doi: 10.1016/S0140-6736(12)62167-9.

[9] E. van der Kruk, A. K. Silverman, L. Koizia, P. Reilly, M. Fertleman, and A. M. J. Bull, “Age-related compensation: Neuromusculoskeletal capacity, reserve & movement objectives,” *J Biomech*, vol. 122, Jun. 2021, doi: 10.1016/j.jbiomech.2021.110385.

[10] E. van der Kruk, A. K. Silverman, P. Reilly, and A. M. J. Bull, “Compensation due to age-related decline in sit-to-stand and sit-to-walk,” *Journal of Biomechanics*, vol. 122. Elsevier Ltd, Jun. 09, 2021. doi: 10.1016/j.jbiomech.2021.110411.

[11] B. Barenius, S. Ponzer, A. Shalabi, R. Bujak, L. Norlén, and K. Eriksson, “Increased risk of osteoarthritis after anterior cruciate ligament reconstruction: A 14-year follow-up study of a randomized controlled trial,” *American Journal of Sports Medicine*, vol. 42, no. 5, pp. 1049–1057, 2014, doi: 10.1177/0363546514526139.

[12] P. M. Dall and A. Kerr, “Frequency of the sit to stand task: An observational study of free-living adults,” *Appl Ergon*, vol. 41, no. 1, pp. 58–61, 2010, doi: 10.1016/j.apergo.2009.04.005.

[13] K. M. Kerr, B. A. Mcsp’, J. A. White, D. A. B. Phd4, and R. A. B. Mollan, “Standardization and definitions of the sit-stand-sit movement cycle,” 1994.

[14] M. Janssen, J. Harlaar, B. Koopman, and I. D. Groot, “Unraveling upper extremity performance in Duchenne muscular dystrophy: A biophysical model,” *Neuromuscular Disorders*, vol. 29, pp. 368–375, 2019.

[15] M. F. Bobbert, D. A. Kistemaker, M. A. Vaz, and M. Ackermann, “Searching for strategies to reduce the mechanical demands of the sit-to-stand task with a muscle-actuated optimal control model,” *Clinical Biomechanics*, vol. 37, pp. 83–90, Aug. 2016, doi: 10.1016/j.clinbiomech.2016.06.008.

[16] S. Bajelan and M. R. Azghani, “Musculoskeletal modeling and simulation of three various Sit-to-Stand strategies: An evaluation of the biomechanical effects of the chair-rise strategy modification,” *Technology and Health Care*, vol. 22, no. 4, pp. 627–644, 2014, doi: 10.3233/THC-140834.

[17] S. H. L. Smith, P. Reilly, and A. M. J. Bull, “A musculoskeletal modelling approach to explain sit-to-stand difficulties in older people due to changes in muscle recruitment and movement strategies,” *J Biomech*, vol. 98, Jan. 2020, doi: 10.1016/j.jbiomech.2019.109451.

[18] E. van der Kruk, P. Strutton, L. J. Koizia, M. Fertleman, P. Reilly, and A. M. J. Bull, “Why do older adults stand-up differently to young adults?: investigation of compensatory movement strategies in sit-to-walk,” *npj Aging*, vol. 8, no. 1, Sep. 2022, doi: 10.1038/s41514-022-00094-x.

[19] M. Hendriksen, “Musculoskeletal Modelling of Three Sit-to-Stand Strategies in Elderly People.”

[20] V. Kumar, T. Yoshiike, and T. Shibata, “Predicting Sit-to-Stand Adaptations due to Muscle Strength Deficits and Assistance Trajectories to Complement Them,” *Front Bioeng Biotechnol*, vol. 10, Mar. 2022, doi: 10.3389/fbioe.2022.799836.

[21] S. W. Smith, “Quantifying musculoskeletal reserve in the elderly,” 2017.

[22] D. S. Komaris, C. Govind, A. Murphy, A. Ewen, and P. Riches, “Identification of movement strategies during the sit-to-walk movement in patients with knee osteoarthritis,” *J Appl Biomech*, vol. 34, no. 2, pp. 96–103, Apr. 2018, doi: 10.1123/jab.2016-0279.

[23] T. Burner *et al.*, “Shoulder symptoms and function in geriatric patients,” *Journal of Geriatric Physical Therapy*, vol. 37, no. 4, pp. 154–158, Oct. 2014, doi: 10.1519/JPT.0b013e3182abe7d6.

[24] S. L. Delp *et al.*, “OpenSim: Open-source software to create and analyze dynamic simulations of movement,” *IEEE Trans Biomed Eng*, vol. 54, no. 11, pp. 1940–1950, Nov. 2007, doi: 10.1109/TBME.2007.901024.

[25] A. Rajagopal, C. L. Dembia, M. S. DeMers, D. D. Delp, J. L. Hicks, and S. L. Delp, “Full-Body Musculoskeletal Model for Muscle-Driven Simulation of Human Gait,” *IEEE Trans Biomed Eng*, vol. 63, no. 10, pp. 2068–2079, Oct. 2016, doi: 10.1109/TBME.2016.2586891.

[26] A. Seth, M. Dong, R. Matias, and S. Delp, “Muscle contributions to upper-extremity movement and work from a musculoskeletal model of the human shoulder,” *Front Neurorobot*, vol. 13, 2019, doi: 10.3389/fnbot.2019.00090.

[27] T. Hu, J. Kühn, and S. Haddadin, “Forward and inverse dynamics modeling of human shoulder-arm musculoskeletal system with scapulothoracic constraint,” *Comput Methods Biomech Biomed Engin*, vol. 23, no. 11, pp. 785–803, Aug. 2020, doi: 10.1080/10255842.2020.1764945.

[28] F. V. D. Helm, “A finite element musculoskeletal model of the shoulder mechanism.,” *J Biomech*, vol. 27, pp. 551–569, 1994.

[29] M. D. K. Breteler, C. Spoor, and F. V. D. van der Helm, “Measuring muscle and joint geometry parameters of a shoulder for modeling purposes.,” *J Biomech*, vol. 32 11, pp. 1191–1197, 1999.

[30] D. Winter, “Biomechanics and Motor Control of Human Movement,” 1990.

[31] J. Hicks, “Simulation with OpenSim - Best Practices - OpenSim Documentation - Global Site.” 2017. [Online]. Available: https://simtk-confluence.stanford.edu:8443/display/OpenSim/Simulation+with+OpenSim+-+Best+Practices

[32] J. A. I. Prinold and A. M. J. Bull, “Scapula kinematics of pull-up techniques: Avoiding impingement risk with training changes,” *J Sci Med Sport*, vol. 19, no. 8, pp. 629–635, Aug. 2016, doi: 10.1016/j.jsams.2015.08.002.

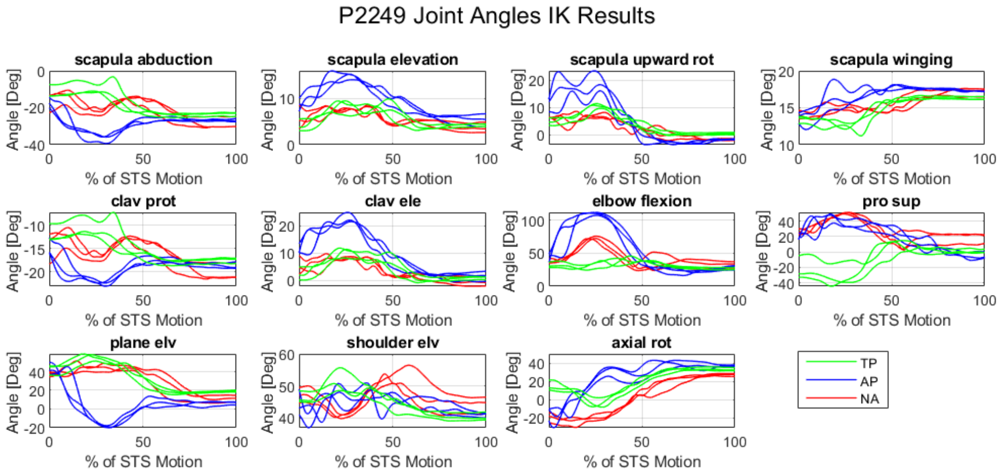
APPENDIX A

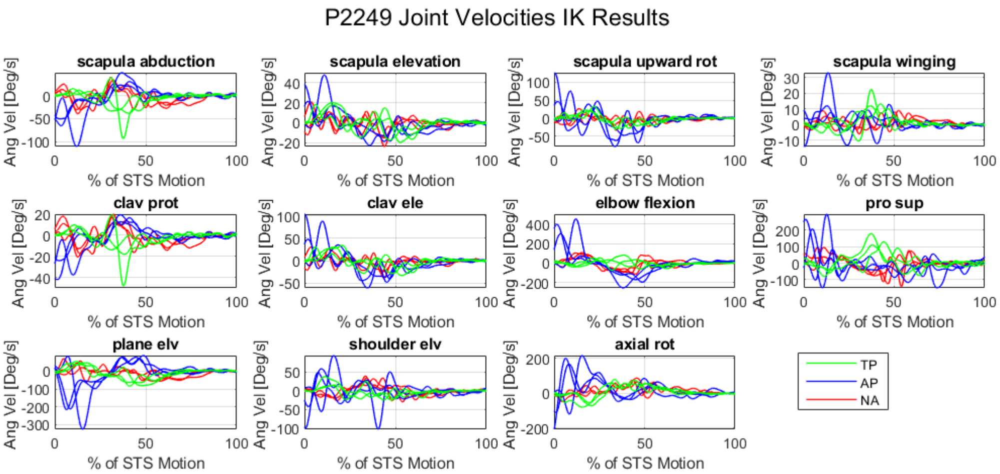
Anatomical Locations of the Reflective Markers. Total Number of Markers = 65

Segment	Markers	Nr.	Anatomical location	Bilateral Yes/No
Thorax	C7	1	7th cervical vertebra	No
	T8	2	8th thoracic vertebra	No
	IJ	3	Sternum jugular notch	No
	MA	4	Sternum manubrium	No
	PX	5	Sternum xiphoid process	No
Pelvis	RASIS	6	Right anterior superior iliac spine	No
	LASIS	7	Left anterior superior iliac spine	No
	RPSIS	8	Right posterior superior iliac spine	No
	LPSIS	9	Left posterior superior iliac spine	No
	P1, P2, P3	10	Cluster of three markers placed on the pelvis	No
Clavicle	RA	11	Right acromioclavicular joint	No
	SC	12	Sternoclavicular joint	Yes
Scapula	S1, S2, S3	13	Scapula trackers (3 markers) placed on the scapula spine	No
Humerus	HU1, HU2, HU3, HU4	14	Cluster of four markers placed on the upper arm	No
	LE	15	Lateral epicondyle	No
	ME	16	Medial epicondyle	No
Forearm	U1, U2, U3, U4	17	Cluster of four markers placed on the forearm	No
	US	18	Ulnar styloid	No
	RS	19	Radial styloid	No
Hand	H1, H2, H3	20	Cluster of three markers placed on the back of the hand	No
Foot	FM2	21	Head of the second metatarsal	Yes
	FCC	22	Calcaneus	Yes
	FMT	23	Tuberosity of the fifth metatarsal	Yes
	TF	24	Additional marker placed on the foot	Yes
	FAM	25	Apex of the lateral malleolus	Yes
	TAM	26	Apex of the medial malleolus	Yes
Shank	C1, C2, C3, C4	27	Cluster of four markers placed on the calf segment	Yes
Knee	FLE	28	Lateral femoral epicondyle	Yes
	FME	29	Medial femoral epicondyle	Yes
Thigh	T1, T2, T3, T4	30	Cluster of four markers placed on the thigh segment	Yes

APPENDIX B

This appendix shows the IK Results of a single participant for the coordinates present in the upper extremity. Each graph contains all trials performed for every strategy and show the angles and velocities attained by every coordinate present in the upper extremity during the STS motion.





APPENDIX C

Averaged peak force exerted with the on the force plates. Forces are shown in N/kg

Eternal Force	Strategy	EM	EF	YM
Right Floor	TP	0.67 ± 0.11	0.66 ± 0.05	0.67 ± 0.04
	AP	0.58 ± 0.12	0.61 ± 0.07	0.67 ± 0.12
	NA	0.6 ± 0.13	0.65 ± 0.13	0.68 ± 0.06
Left Floor	TP	0.72 ± 0.18	0.70 ± 0.2	0.62 ± 0.03
	AP	0.66 ± 0.2	0.63 ± 0.23	0.63 ± 0.13
	NA	0.7 ± 0.2	0.67 ± 0.18	0.62 ± 0.05
Right Thigh	TP	0.52 ± 0.11	0.58 ± 0.48	1.38 ± 1.82
	AP	0.49 ± 0.12	0.55 ± 0.37	1.26 ± 1.63
	NA	0.48 ± 0.08	0.69 ± 0.82	1.10 ± 1.29
Left Thigh	TP	0.59 ± 0.09	0.64 ± 0.10	1.65 ± 2.28
	AP	0.58 ± 0.15	0.65 ± 0.15	1.36 ± 1.68
	NA	0.6 ± 0.15	0.79 ± 0.48	1.20 ± 1.48
Right Hand	TP	0.13 ± 0.04	0.11 ± 0.02	0.162 ± 0.05
	AP	**0.2 ± 0.06** [a, c]	0.12 ± 0.08	**0.155 ± 0.11** [a, c]
	NA	[ ]	[ ]	[ ]

a <0,05 between the TP and AP strategy per group
b <0,05 between the TP and NA strategy per group
c <0,05 between EM-EF, and EM-YM per strategy

APPENDIX D

Averaged Peak Muscle Forces for each Participant Group. Forces are shown in N/BW

Muscle	Strategy	EM	EF	YM
Trapezius Scapula M	TP	0.01 ± 0.01	0.01 ± 0.00	0.01 ± 0.00
	AP	0.02 ± 0.02	0.02 ± 0.01	0.01 ± 0.01
	NA	0.01 ± 0.00	0.01 ± 0.01	0.01 ± 0.00
Trapezius Scapula S	TP	0.16 ± 0.09	0.14 ± 0.09	0.08 ± 0.02
	AP	0.21 ± 0.18	0.17 ± 0.16	0.17 ± 0.28
	NA	0.11 ± 0.05	0.11 ± 0.03	0.06 ± 0.02
Trapezius Scapula I	TP	0.01 ± 0	0.01 ± 0	0.01 ± 0
	AP	0.02 ± 0.02	0.02 ± 0.01	0.01 ± 0.01
	NA	0.01 ± 0	0.01 ± 0.01	0 ± 0
Trapezius Clavicle S	TP	0.06 ± 0.01	0.05 ± 0.03	0.07 ± 0.01
	AP	**0.11 ± 0.03** [a]	0.08 ± 0.03	0.12 ± 0.04
	NA	0.07 ± 0.03	0.05 ± 0.02	**0.08 ± 0.02** [c]
Serratus Anterior I	TP	0.02 ± 0.01	0.03 ± 0.01	0.02 ± 0.02
	AP	0.04 ± 0.04	0.04 ± 0.03	0.04 ± 0.05
	NA	0.02 ± 0.01	0.03 ± 0.01	0.01 ± 0
Serratus Anterior M	TP	0.14 ± 0.03	0.14 ± 0.05	0.15 ± 0.09
	AP	**0.19 ± 0.08** [a]	0.14 ± 0.07	0.18 ± 0.16
	NA	**0.10 ± 0.02** [c]	0.1 ± 0.01	0.07 ± 0.02
Serratus Anterior S	TP	0.01 ± 0.01	0.02 ± 0.01	0.01 ± 0
	AP	0.02 ± 0.01	0.03 ± 0.01	0.01 ± 0.01
	NA	0.01 ± 0	0.02 ± 0.01	0.01 ± 0
Rhomboideus S	TP	0.01 ± 0.01	0.01 ± 0	0.01 ± 0
	AP	0.01 ± 0	0.02 ± 0.01	0.01 ± 0
	NA	0.01 ± 0	0.01 ± 0	0.01 ± 0
Rhomboideus I	TP	0.01 ± 0	0.02 ± 0.01	0.01 ± 0
	AP	**0.03 ± 0.03** [a]	0.04 ± 0.02	0.01 ± 0.01
	NA	**0.01 ± 0** [c]	0.02 ± 0.01	0.01 ± 0.01
Levator Scapulae	TP	0.09 ± 0.03	0.07 ± 0.02	0.07 ± 0.05
	AP	0.08 ± 0.05	0.09 ± 0.03	0.06 ± 0.02
	NA	**0.05 ± 0.01** [c]	**0.06 ± 0.01** [c]	0.05 ± 0.02
Coracobrachialis	TP	0.09 ± 0.05	0.1 ± 0.04	0.07 ± 0.05
	AP	**0.28 ± 0.22** [a]	**0.12 ± 0.08** [d]	**0.24 ± 0.32** [d]
	NA	**0.07 ± 0.05** [c]	0.08 ± 0.02	0.05 ± 0.02
Deltoideus Clavicle A	TP	0.45 ± 0.36	0.37 ± 0.22	0.34 ± 0.16
	AP	0.54 ± 0.41	0.26 ± 0.3	**0.47 ± 0.31** [a]
	NA	0.19 ± 0.13	**0.14 ± 0.04** [b]	**0.15 ± 0.06** [b]
Deltoideus Scapula P	TP	0.30 ± 0.31	0.2 ± 0.21	0.10 ± 0.05
	AP	0.34 ± 0.15	0.1 ± 0.03	0.19 ± 0.11
	NA	0.15 ± 0.12	0.09 ± 0.04	0.13 ± 0.07
Deltoideus Scapula M	TP	0.24 ± 0.05	0.27 ± 0.1	0.19 ± 0.07
	AP	**0.81 ± 0.54** [a]	**0.59 ± 0.26** [a]	**0.66 ± 0.56** [a]
	NA	**0.24 ± 0.07** [c]	**0.21 ± 0.04** [c]	**0.22 ± 0.03** [c]
Latissimus Dorsi S	TP	0 ± 0	0.01 ± 0	0.00 ± 0.00
	AP	**0.01 ± 0.01** [a]	**0.01 ± 0.01** [a]	0.01 ± 0.00
	NA	**0 ± 0** [c]	**0.01 ± 0** [c]	0 ± 0
Latissimus Dorsi M	TP	0.01 ± 0	0.01 ± 0	0 ± 0
	AP	**0.03 ± 0.02** [a]	**0.02 ± 0.02** [a]	0.02 ± 0.02
	NA	**0.01 ± 0** [c]	**0.01 ± 0** [c]	0.01 ± 0
Latissimus Dorsi I	TP	0 ± 0	0.01 ± 0	0 ± 0
	AP	**0.02 ± 0.02** [a]	**0.02 ± 0.01** [a]	0.02 ± 0.05

	NA	**0 ± 0** [c]	**0 ± 0** [c]	0 ± 0
Pectoralis Major Clavicle S	TP	0.22 ± 0.11	0.13 ± 0.05	0.14 ± 0.09
	AP	0.28 ± 0.12	0.12 ± 0.08	0.27 ± 0.19
	NA	**0.09 ± 0.04** [b, c]	0.07 ± 0.02	0.09 ± 0.03
Pectoralis Major Torso I	TP	0.05 ± 0.02	0.05 ± 0.03	0.04 ± 0.06
	AP	**0.25 ± 0.14** [a]	**0.15 ± 0.13** [a]	**0.23 ± 0.26** [d]
	NA	**0.01 ± 0** [c]	**0.02 ± 0.01** [c]	0.01 ± 0
Pectoralis Major Torso M	TP	0.31 ± 0.19	0.18 ± 0.07	0.15 ± 0.22
	AP	0.46 ± 0.16	**0.23 ± 0.19** [d]	**0.3 ± 0.3** [d]
	NA	**0.08 ± 0.05** [b, c]	**0.04 ± 0.03** [c]	**0.06 ± 0.04** [c]
Teres Major	TP	0.2 ± 0.18	0.14 ± 0.11	0.06 ± 0.03
	AP	**0.46 ± 0.31** [a]	**0.35 ± 0.17** [a]	**0.32 ± 0.17** [a]
	NA	**0.08 ± 0.06** [c]	**0.06 ± 0.02** [c]	**0.08 ± 0.03** [c]
Infraspinatus I	TP	0.17 ± 0.06	0.11 ± 0.03	0.07 ± 0.01
	AP	0.2 ± 0.16	0.11 ± 0.04	0.12 ± 0.05
	NA	0.13 ± 0.06	0.09 ± 0.02	0.08 ± 0.03
Infraspinatus S	TP	0.08 ± 0.04	0.09 ± 0.02	0.06 ± 0.01
	AP	**0.23 ± 0.2** [a]	**0.22 ± 0.14** [a]	0.24 ± 0.34
	NA	**0.08 ± 0.03** [c]	**0.07 ± 0.02** [c]	0.06 ± 0.01
Pectoralis Minor	TP	0.01 ± 0	0.01 ± 0	0.01 ± 0
	AP	**0.03 ± 0.01** [a]	**0.03 ± 0.02** [a]	0.01 ± 0.01
	NA	**0.01 ± 0** [c]	**0.01 ± 0** [c]	0.01 ± 0
Teres Minor	TP	0.06 ± 0.05	0.05 ± 0.01	0.03 ± 0.01
	AP	0.09 ± 0.04	0.06 ± 0.02	0.07 ± 0.02
	NA	0.06 ± 0.03	0.05 ± 0.01	0.04 ± 0.01
Subscapularis S	TP	0.07 ± 0.02	0.06 ± 0.01	0.04 ± 0.01
	AP	**0.15 ± 0.04** [a]	**0.14 ± 0.07** [a]	0.13 ± 0.11
	NA	**0.04 ± 0.01** [c]	**0.04 ± 0.01** [c]	0.03 ± 0.02
Subscapularis M	TP	0.06 ± 0.03	0.04 ± 0.01	0.03 ± 0.01
	AP	**0.13 ± 0.05** [a]	**0.08 ± 0.04** [a]	0.1 ± 0.08
	NA	**0.03 ± 0.01** [c]	**0.03 ± 0.01** [c]	0.03 ± 0.01
Subscapularis I	TP	0.17 ± 0.08	0.11 ± 0.05	0.07 ± 0.03
	AP	**0.33 ± 0.16** [a]	**0.24 ± 0.13** [a]	0.22 ± 0.15
	NA	**0.08 ± 0.03** [c]	**0.07 ± 0.02** [c]	0.07 ± 0.03
Supraspinatus P	TP	0.03 ± 0.01	0.03 ± 0.01	0.02 ± 0.01
	AP	**0.07 ± 0.06** [a]	0.04 ± 0.04	0.08 ± 0.1
	NA	**0.02 ± 0.01** [c]	0.03 ± 0.01	0.02 ± 0.01
Supraspinatus A	TP	0.07 ± 0.02	0.08 ± 0.03	0.05 ± 0.02
	AP	**0.19 ± 0.18** [a]	0.13 ± 0.13	0.14 ± 0.16
	NA	**0.06 ± 0.02** [c]	0.06 ± 0.02	0.05 ± 0.01
Triceps Longhead	TP	0.17 ± 0.07	0.18 ± 0.05	0.18 ± 0.05
	AP	0.59 ± 0.8	0.29 ± 0.27	0.3 ± 0.29
	NA	0.22 ± 0.07	0.15 ± 0.06	0.2 ± 0.04
Biceps Longhead	TP	0.05 ± 0.02	0.04 ± 0.02	0.02 ± 0.01
	AP	0.06 ± 0.07	0.04 ± 0.06	0.07 ± 0.13
	NA	0.03 ± 0.02	0.02 ± 0.02	0.02 ± 0.01
Biceps Shorthead	TP	0.06 ± 0.01	0.06 ± 0.02	0.07 ± 0.01
	AP	0.04 ± 0.04	**0.03 ± 0.01** [a]	**0.06 ± 0.06** [a]
	NA	0.06 ± 0.04	0.05 ± 0.03	**0.05 ± 0.02** [c]

a <0,05: Significant difference between the TP and AP strategy per group
b <0,05: Significant difference between the TP and NA strategy per group
c <0,05: Significant difference between the AP and NA strategy per group
d <0,05: Significant difference between EM-EF, and EM-YM per strategy

APPENDIX E

This appendix shows an example of a comparison of the IK results of Hendriksen and this study. The legend shows either D or H, corresponding to Dielissen or Hendriksen, along with the strategy. The graphs include the joint angles and velocities of several coordinates of the lower limb over the STS motion.