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CHAPTER 5

THREE DIMENSIONAL MUSCULOSKELETAL MODELLING OF THE SEATED ROW RESISTANCE TRAINING EXERCISE FOCUSING ON THE BIOMECHANICAL AND ANTHROPOMETRIC CONSIDERATIONS OF THE END-USER

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Abstract

The aim of this study was to evaluate whether three dimensional (3D) musculoskeletal modelling could be effective in assessing the safety and efficacy of exercising on a seated row resistance training machine. The focus of the evaluation was on biomechanical and anthropometric considerations of the end-user. Three anthropometric cases were created; these represented a 5th percentile female as well as a 50th and 95th percentile male based on body mass index (BMI). Resistance on the seated row machine was set at fifty percent of the functional strength one repetition maximum (1RM) for each anthropometric case, two repetitions were performed. Results indicate that the default model of the Lifemodeler™ software has important limitations which should be taken into consideration when being used to evaluate exercise equipment. Adjustments had to be made to the model in order to solve the forward dynamics simulations and as a result no muscle forces or contraction values were obtained. This negatively influenced the value of the results as these parameters are important when analysing an exercise. The seated row resistance training machine's engineered or manufactured adjustability was sufficient as it appeared to accommodate the three anthropometric cases adequately so that no substantial injury risk was established for this exercise.

Keywords: *Resistance training equipment, seated row, biomechanics, anthropometric, modelling, Lifemodeler^{TM}, inverse dynamics, forward dynamics*

Introduction

This article constitutes the third article in a series of four. The series consists of three dimensional (3D) musculoskeletal modelling with a focus on biomechanical and anthropometric variables of four commonly used pieces of resistance training equipment.

The advancement in computer technology and data processing capability has allowed the improvement of modelling software to a point where dynamic problems can now be simulated and analysed in a digital environment (Kim and Martin, 2007; Wagner *et al*., 2007; Zenk *et al*., 2005). Furthermore, computer simulations allow for the exploration of the limitations of human movement systems without endangering human subjects (Luttgens *et al*., 1992). With the capability to simulate musculoskeletal human models interacting with mechanical systems many questions concerning the effects of the resistance training equipment on the body can be studied.

This study presents the musculoskeletal modelling of three anthropometric cases while exercising on a seated row resistance training machine. Thus, the primary aim of this study was to determine the efficacy of 3D musculoskeletal modelling in evaluating resistance training equipment design such as the seated row resistance training machine.

In recent years, the popularity of dynamic resistance training has risen. This type of training is suitable for developing muscular fitness of men and women of all ages, as well as children (Heyward, 2004). The seated row forms the basis of many land-based training programmes for athletes, more specifically rowers. However, it is also often included as part of strength training programmes for non-athletes. It is an effective exercise to strengthen the musculature of the upper back. The primary joint movements for this exercise are shoulder extension and elbow flexion and thus the prime movers include the Latissimus dorsi and the Biceps brachii muscles (Heyward, 2004). Other important muscles involved in the seated row exercise are the Posterior deltoids, Trapezius and Rhomboideus muscle groups (Floyd, 2009). In terms of understanding the biomechanics associated with various resistance training exercises, a great deal of literature has investigated the kinetics and kinematics associated with the bench press, squat and Olympic lifts. Therefore, it would appear as there is a preoccupation of researchers with extension type tasks and very little attention is given to other movements (Cronin *et al,* 2007). Furthermore, much of the available research consists of rowing ergometer analysis rather than the seated row resistance exercise.

Methods

Equipment

A 3D musculoskeletal full body model was created using LifeModeler™ software and incorporated into a multibody dynamics model of the seated row resistance machine modelled in MSC ADAMS (Figure 1). The LifeModeler™ software runs as a plug-in on the MSC ADAMS software. LifeModeler™ software has previously been used in studies in the fields of sport, exercise and medicine (Schillings *et al*., 1996; Rietdyk and Patla, 1999; Hofmann *et al*., 2006; Agnesina *et al*., 2006; De Jongh, 2007; Olesen *et al*., 2009). It was decided to evaluate a default model as generated through the software. This model consists of 19 segments including a base set of joints for each body region. Specifically, the spine does not consist of individual vertebrae but rather of various segments that represent different regions of the vertebral column with joints between these segments. Furthermore, the default model has a full body set of 118 muscle elements attached to the bones at anatomical landmarks, which includes most of the major muscle groups in the body. Closed loop simple muscles were modelled. Closed loop muscles contain proportional-integral-differential (PID) controllers. The PID controller algorithm uses a target length-time curve to generate the muscle activation and the muscles follow this curve. Because of this approach, an inverse dynamics simulation using passive recording muscles is required prior to simulation with closed loop muscles. Simple muscles fire with no constraints except for the physiological cross-sectional area (pCSA), which designates the maximum force a muscle can exert. The graphs of simple muscle activation curves will generally peak at a flat force ceiling value (Biomechanics research group, 2006).

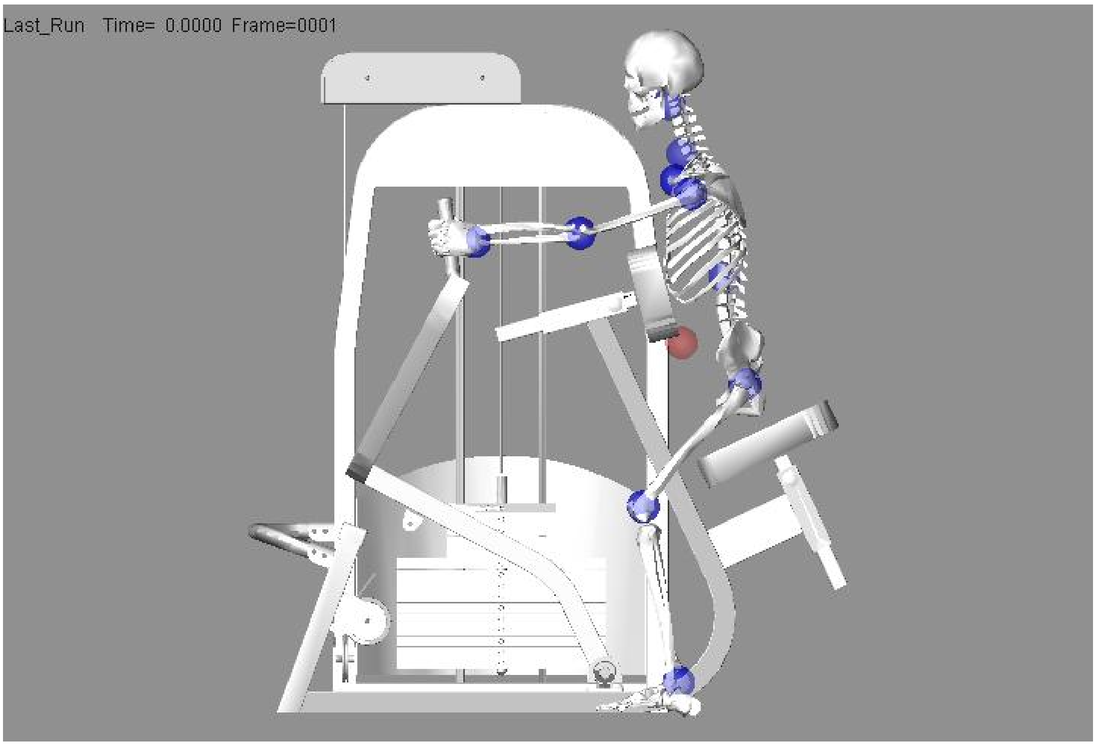

Figure 1. 3D musculoskeletal modelling of the seated row resistance training machine and 50th percentile male musculoskeletal model using LifeModeler™ and MSC ADAMS software.

Musculoskeletal full body human and seated row computer aided design (CAD) models

Three anthropometric cases were created for each piece of equipment. The human models were created using the GeBOD anthropometry database (default LifeModeler™ database) but were based on body mass index (BMI) data obtained from RSA-MIL-STD 127 Vol 1 (2004). This standard is a representative anthropometry standard of the South African National Defence Force which is kept current by a yearly sampling plan and is an accurate representation of the broader South Africa population. Bredenkamp (2007) described a process to characterize the body forms of SANDF males and females. Body form variances described by two principle components (PC's) for the SANDF males and two PC's for SANDF females were included in the modelling process. Positive and negative boundary cases of each PC, representing the boundary conditions to be accommodated in design (Gordon and Brantley, 1997), identified the total range of four male and four female models. It was decided to use the cases representing the smallest female as well as an average and large male for the three anthropometric cases for this study. These cases could be seen as what are traditionally known as a 5th percentile female, 50th percentile male and a 95th percentile male based on the BMI of each of these cases. Thus, for the purpose of building these biomechanical models, a correlation between BMI and functional body strength was assumed. Similar assumptions have previously been made in biomechanics full body model simulations (Rasmussen *et al.,* 2007). A study by Annegarn *et al.* (2007) also verified scaled modelling strengths against actual functional body strengths and correlations ranged from 0.64 to 0.99.

This approach was followed in order to ensure that the equipment can accommodate an acceptable sample of the South African end-user population. A CAD model of the seated row resistance training machine was obtained from a South African exercise equipment manufacturing company. The model in a Parasolid file format was imported into the LifeModeler™ simulation software.

The Adams software was used to create two design variables in order to adjust the external resistance (as selected by the amount of weights when using a selectorised resistance training machine) and to specify the radius of the cam over which the cable of an actual exercise machine would run in order to lift the selected resistance. This was possible since this machine employed a circular cam system however, this would not be possible with exercise machines employing non-circular cam systems, in order to attain better mechanical advantage for the end-user. A special contact force (solid to solid) was created between the weights being lifted and the remainder of the weight stack during the simulation. A coupler joint was created linking the revolute joint (driver) of the lever arm attached to the handle bars with the translational joint of the weight stack. The design variable created for the radius of the cam was referenced as the scale of the coupled joint (translational joint at weights). The design variable created for the mass of the weights was then adjusted according to the pre-determined resistance for each anthropometric case.

The external resistance applied in the models was based on data obtained from RSA-MIL-STD 127 Vol 5 (2001). This database consists of a range of human functional strength measurement variables for SANDF males and females. Due to its representivity this standard may be considered an accurate representation of the functional body strength of the South Africa population (RSA-MIL-STD-127, 2001). Furthermore, functional strength data was used from activities that most closely resembled the movements of the exercise as well as the muscle groups used during such movement. Fifty percent of the functional strength one repetition maximum (1RM) for each anthropometric case was used as this can be considered a manageable resistance to perform an exercise with appropriate form and technique for two repetitions.

Simulation

Extreme care was taken with the positioning of the musculoskeletal model onto the seated row machine to ensure technique, posture and positioning was correct according to best exercise principles (Table I). Optimal positioning of the models on the equipment required that there was approximately 90 degrees of shoulder flexion with slight elbow flexion that resulted in the hands finally being just higher than the elbows for all the anthropometric cases. This would be considered the correct posture for this exercise and resulted in the handle height being just below shoulder level for all the cases. Furthermore, total manufacturer adjustability of the exercise machine was used in order to ensure correct positioning for each of the anthropometric cases. The following steps were performed in order to ensure realistic kinematics during the inverse dynamics simulations: 1) Positioning of the human model on the exercise equipment, 2) Adjustment of the posture to allow for the human machine interface to be created, 3) Creating the constraints between the human and machine, 4) Prescribing the motion of the repetitions, 5) Evaluation of the resultant kinematics, 6) Adjustment of joint positions until inverse dynamics resulted in a realistic exercise movement. Bushing elements were used to secure the chest to the chest pad/cushion as well as the lower torso to the seat and spherical joints were used to connect the hands to the handle bars of the seated row machine. Bushing elements were preferred to fixed joint elements because it allows for limited translational and rotational motion. Also, the amount of motion can be controlled by changing stiffness and damping characteristics in all 3 orthogonal directions. The original joints created in the biomechanical model had default joint parameters (Stiffness (K) =1E4, Dampening (C) =1000). Joints with such high joint stiffness are created to ensure a relatively "rigid" model that provides a stable and smooth motion when manipulated by motion splines. This is especially important during the movement of the model into the initial posture as well as to ensure smooth model motion during inverse dynamics. After the muscle lengths had been recorded in the inverse dynamics, the joint stiffness was changed to near zero, to represent actual stiffness in human joints.

The inverse dynamics – forward dynamics method was applied during the simulations. Inverse dynamics simulations are performed on models which are being manipulated by the use of motion agents or motion spines. During the inverse dynamics simulation, a rotational motion was applied to the revolute joint of the lever arm attached to the handle bars of the seated row machine in order to generate the required movement of the resistance training machine. This movement replicated the pulling (concentric) and resisting (eccentric) phase of the exercise. The time for the concentric phase was set at 1.66 seconds and the eccentric phase longer at 3.33 seconds to mimic conventional resistance training technique in which the downward phase is more deliberate to prohibit the use of momentum. The 1.66 second concentric phase included a STEP function approximation over 0.5 seconds to ensure a gradual start to the movement. The joints forces of the model were recorded during the inverse dynamics simulation in order to calculate the changes in joint torques to result in the required machine movement.

After the inverse dynamics simulation was performed, the rotational motion was removed from the rotational joint of the lever arm of the seated row machine. The resulting joint movements were then used to drive the model during the forward dynamics simulation in the manner as developed through the inverse dynamics simulation. During the forward dynamics simulation the model is guided by the internal forces (muscle length changes resulting in joint angulations and torques) and influenced by external forces (gravity, contact and determined exercise resistance). It is important to note that changes had to be made to the LifeModeler^{TM} default model in order to solve the models with plausible kinematics during the forward dynamics simulations. Considering the research problem the detail of these changes will be discussed under the discussions section. All results presented are derived from the forward dynamics simulations after these changes to the default model were made.

Table I. Exercise starting posture for the 3 anthropometric cases on the seated row machine. Where applicable the joint angles refer to bi-lateral joints. Results are presented for the sagittal, transverse and frontal planes (degrees). Note that F = flexion, E = extension, IR = internal rotation and AB = abduction.

Joint	5th percentile female	50th percentile male	95th percentile male
Scapula	0.0; 0.0; .0.0	0.0; 0.0; 0.0	0.0; 0.0; 0.0
Shoulder	85.0(F); 5.0(IR); 7.0(AB)	85.0(F); 5.0(IR); 4.5(AB)	85.0(F); 5.0(IR); 2.5(AB)
Elbow	15.0(F); 10.0(IR); 0.0	15.0(F); 10.0(IR); 0.0	15.0(F); 10.0(IR); 0.0
Wrist	0.0; 0.0; 0.0	0.0; 0.0; 0.0	0.0; 0.0; 0.0
Hip	30.0(F); 0.0; 0.0	35.0(F); 0.0; 0.0	52.0(F); 0.0; 0.0
Knee	30.0(F); 0.0; 0.0	45.0(F); 0.0; 0.0	60.0(F); 0.0; 0.0
Ankle	0.0; 0.0; 0.0	12.0(E); 0.0; 0.0	12.0(E); 0.0; 0.0
Upper neck	0.0; 0.0; .0.0	0.0; 0.0; 0.0	0.0; 0.0; 0.0
Lower neck	0.0; 0.0; .0.0	0.0; 0.0; 0.0	0.0; 0.0; 0.0
Thoracic	0.0; 0.0; .0.0	0.0; 0.0; 0.0	0.0; 0.0; 0.0
Lumbar	15.0(F); 0.0; 0.0	15.0(F); 0.0; 0.0	15.0(F); 0.0; 0.0

Data analysis

The anthropometric dimensions and exercise postures of the musculoskeletal human models were visually assessed in relation to the dimensions and adjustability of the resistance training equipment in order to determine if all three anthropometric cases representative of the South African end-user population could comfortably be accommodated on the seated row resistance training machine. Key aspects included start and end exercise posture as well as maintaining correct technique throughout the exercise during the simulations.

The kinematic and kinetic data from the simulations were analysed specifically in terms of exercise efficacy and peak muscular and joint force production of the prime movers of the seated row exercise. Furthermore, the risk of injury to the musculoskeletal system of the exerciser was ascertained by comparison of measured forces with safe loading limits for joints of the lumbar and thoracic spine. The dynamic mode of analysis includes all the aspects of motion in the calculation of joint forces and internal stresses, including the effects introduced by changing velocity and acceleration components (Wagner *et al.*, 2007). Different joint loading criteria were derived using biomechanical research taking into consideration the posture and anthropometry (Cooper and Ghassemieh, 2007). However, criteria for determining whether a particular task or exercise is "safe" based on tissue-level stresses are available for only a small number of tissues and loading regimes (e.g. lower back motion segments in compression) (Wagner *et al*, 2007).

Due to the nature of this study only basic descriptive statistics were performed by means of the STATISTICA© software package (Statsoft).

Results

Three anthropometric cases created for each piece of equipment based on BMI data obtained from RSA-MIL-STD 127 Vol 1 (2004) were used for the study and results were assessed (Table II). Table III represents the external resistance applied in the models, fifty percent of the functional strength 1RM for each anthropometric case was used for two repetitions.

Table II. Anthropometric details of population groups studied (RSA-MIL-STD, Vol 1, 2004).

User population group	Body mass (kg)	Stature (mm)
5^{th} percentile female	49.5	1500
50^{th} percentile female	66	1610
95^{th} percentile male	85	1840

Table III. User population strength data (RSA-MIL-STD, Vol 5, 2001).

User population group	User population group exercise resistance (50% 1RM) kg
5^{th} percentile female	11
50^{th} percentile male	18
95^{th} percentile male	30

Due to the involvement of wrist, elbow and shoulder joints in the seated row exercise, torque values for these joints are presented in Table IV. Values for the right side of the body are reported on as theoretically the values for the left and right side should be similar. The 95th percentile male recorded the highest peak joint torque values for the three joints (Figures 2, 3 and 4). The 50th percentile male's peak elbow and wrist torque values were the lowest. The peak shoulder torque values of the 5th percentile female and 50th percentile male were similar and were lower than the 95th percentile males values (Figure 4). For the three anthropometric cases the peak shoulder joint torque values were the lowest, followed by the wrist and the greatest for the elbow.

Table IV. Right wrist, elbow and shoulder joint torque (Nm) results in the sagittal plane for the 3 anthropometric cases. Note that the joint torque values presented in the figures are in Nmm due to the default units of the modelling software.

Musculoskeletal model	Joint	Mean (Nm)	Min.	Max.
5th percentile female	Wrist	-1.6	-4.5	0.0
	Elbow	-4.0	-6.3	0.0
	Shoulder	0.9	-1.2	3.2
50th percentile male	Wrist	-1.3	-3.1	0.0
	Elbow	-3.0	-4.7	0.0
	Shoulder	0.2	-1.2	1.9
95th percentile male	Wrist	-0.2	-4.8	2.3
	Elbow	-13.3	-19.5	0.0
	Shoulder	1.7	-2.5	7.0

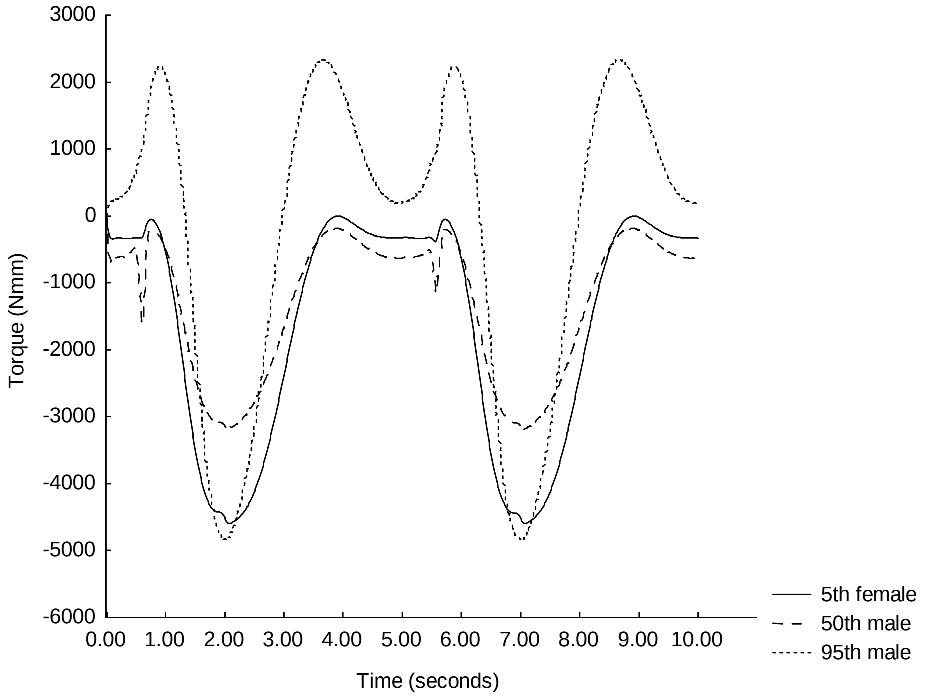

Figure 2. Sagittal right wrist joint torque (Nmm) for the 3 anthropometric cases (2 repetitions).

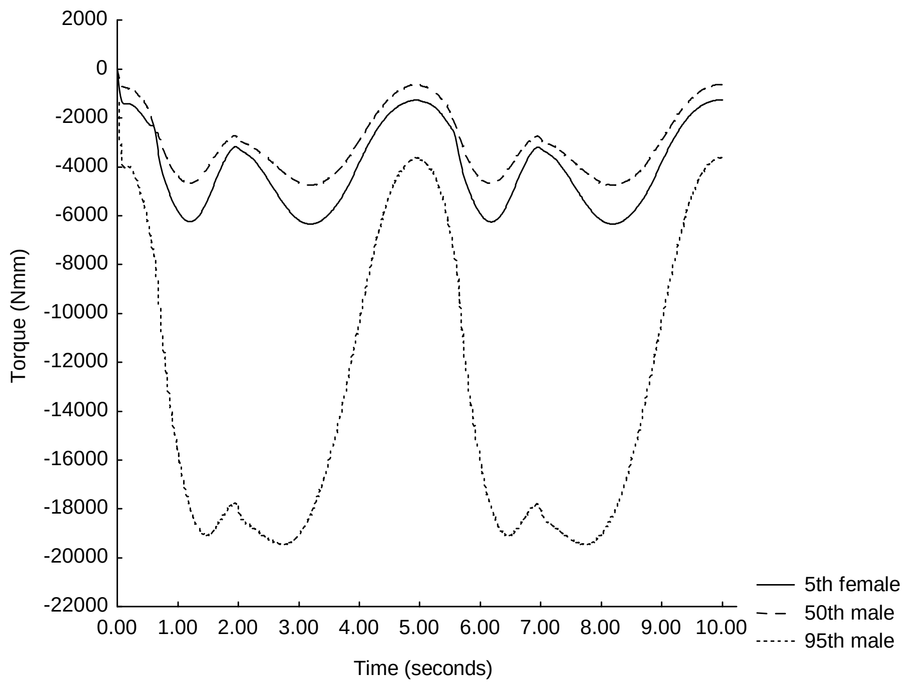

Figure 3. Sagittal right elbow joint torque (Nmm) for the 3 anthropometric cases (2 repetitions).

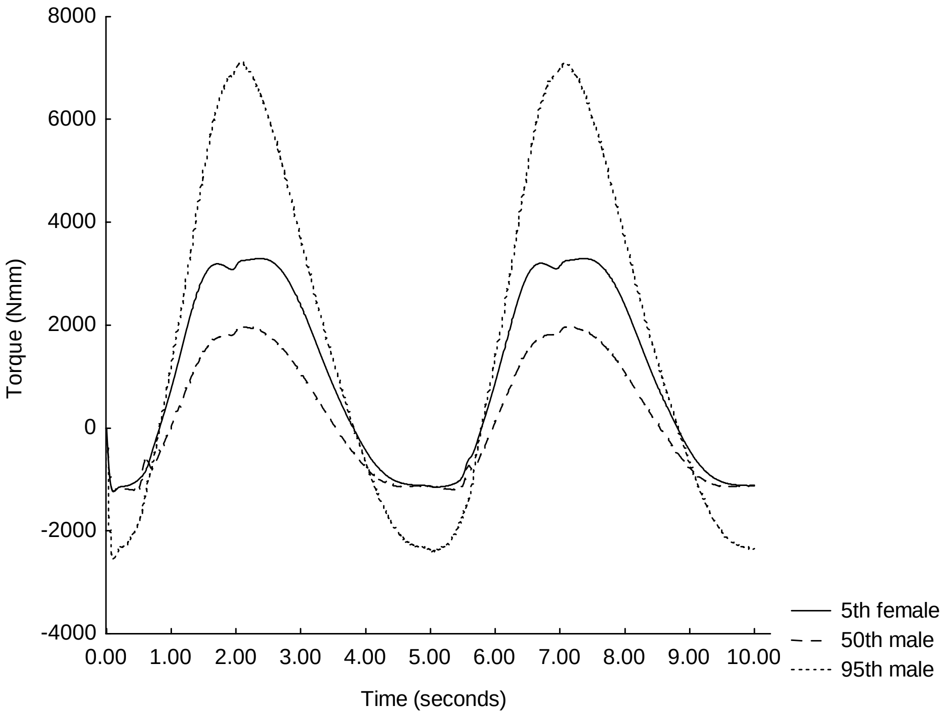

Figure 4. Sagittal right shoulder joint torque (Nmm) for the 3 anthropometric cases (2 repetitions).

The seated row exercise is a multi-joint exercise thus movement in the sagittal plane of the shoulder, elbow and wrist (right side) are reported on (Table V). The least movement occurred at the wrist joint, followed by the shoulder joint with the most movement occurring at the elbow joint for the three anthropometric cases. Range of motion of the 5th percentile female was the least for the three joints. Range of motion was the greatest for the 95th percentile male in the wrist and shoulder joint. Elbow joint range of motion was greatest for the 50th percentile male (Figure 5).

Table V. Sagittal right wrist, elbow and shoulder joint angle (°)

Musculoskeletal model	Joint	Mean (degrees)	Min.	Max.
	Wrist	16.0	0.0	26.5
5th percentile female	Elbow	-75.8	-129.6	-15
	Shoulder	-52.0	-85.0	-16.4
	Wrist	16.3	0.0	27.5
50th percentile male	Elbow	-75.9	-130.5	15.0
	Shoulder	-53.7	-85	-20.8
	Wrist	17.1	0.0	29.0
95th percentile male	Elbow	-73.2	-125.9	-15.0
	Shoulder	-57.8	-85.0	-28.6

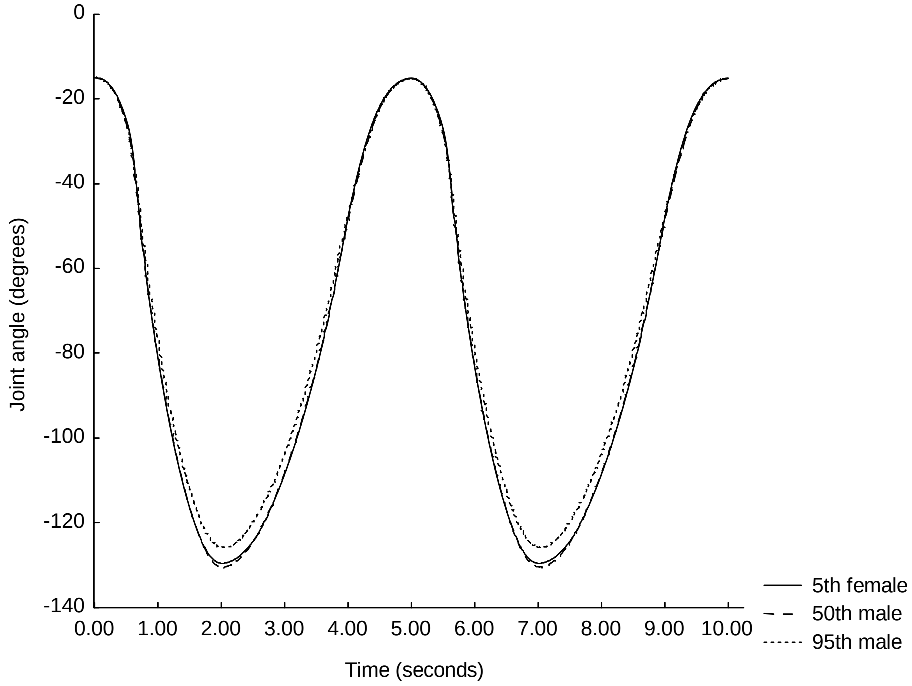

Figure 5. Sagittal right elbow angle (°) for the 3 anthropometric cases (2 repetitions). Note: negative joint angle indicates elbow flexion.

Results for the thoracic (T12/L1 intervertebral joint) and lumbar (L5/S1 intervertebral joint) spine compression and anterior/posterior (A/P) shear forces are presented in Tables VI and VII respectively. Peak thoracic spine joint compression forces were greatest for the 50th percentile male, followed by the 95th percentile male and were lowest in the 5th percentile female (Figure 6). There was a similar trend in the peak lumbar spine joint compression forces

(Figure 7). In all anthropometric cases the peak lumbar spine joint compression forces were greater than the peak thoracic spine joint compression forces.

Table VI. Thoracic and lumbar spine joint compression forces (N) for the 3 anthropometric cases.

Note: positive values indicate forces in a superior direction and negative values indicate forces in an inferior direction.

Musculoskeletal model	Spinal joint	Mean (N)	Min.	Max.
5th percentile female	Thoracic spine	100.3	79.4	149.1
	Lumbar spine	145.0	124.1	193.8
50th percentile male	Thoracic spine	140.0	113.7	168.1
	Lumbar spine	200.0	173.2	227.6
95th percentile male	Thoracic spine	-32.7	-97.1	162.8
	Lumbar spine	28.2	-36.1	223.9

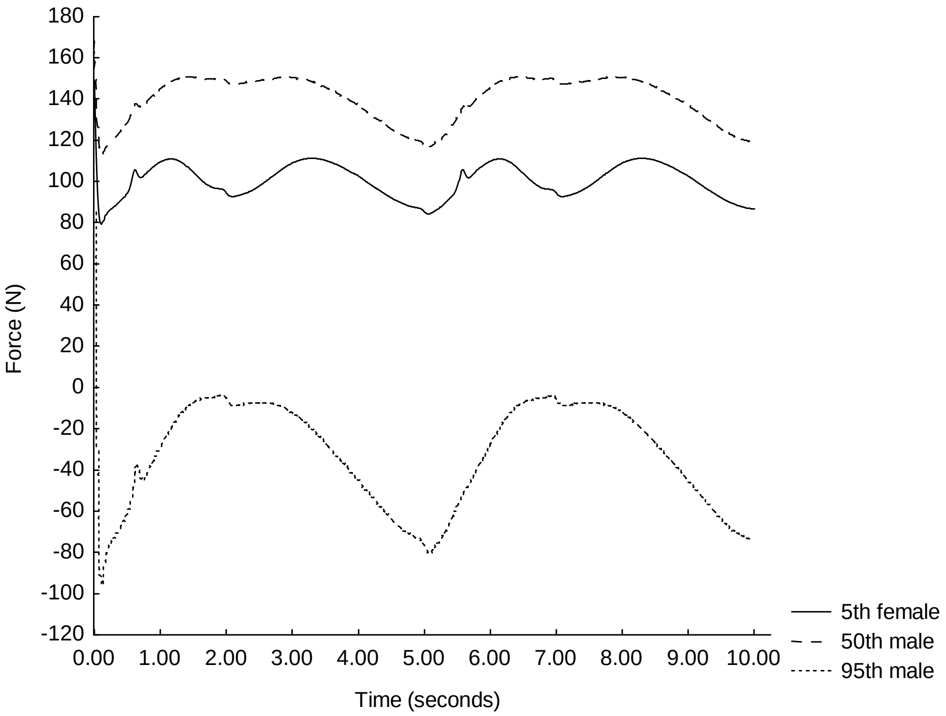

Figure 6. Thoracic spine compression forces (N) for the 3 anthropometric cases (2 repetitions)

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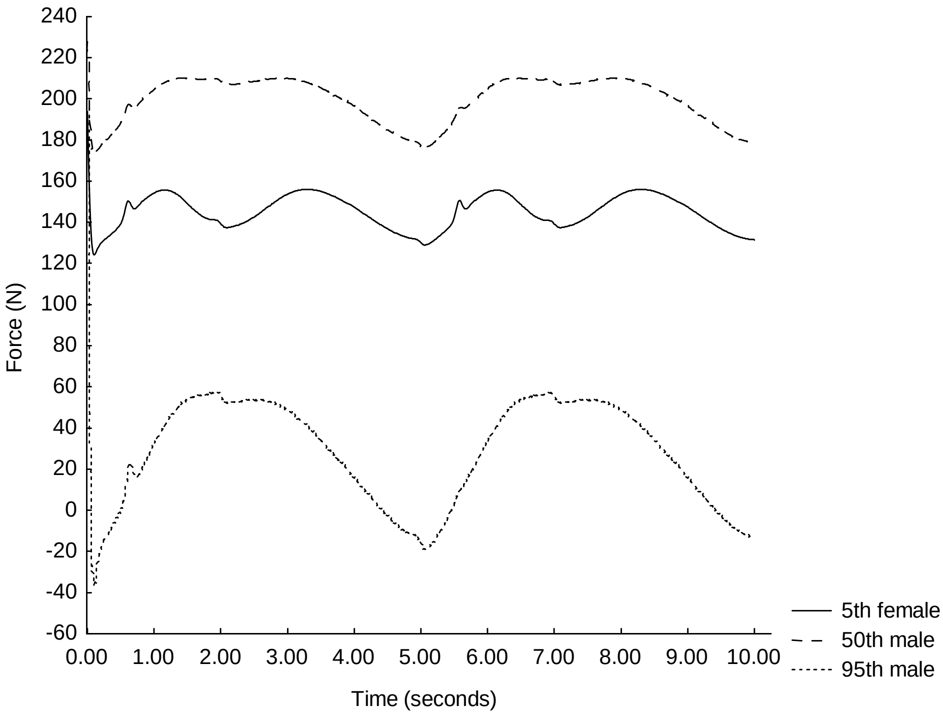

Figure 7. Lumbar spine compression forces (N) for the 3 anthropometric cases (2 repetitions).

The 95th and 50th percentile males recorded similar peak thoracic and lumbar spine A/P shear forces. The 5th percentile females peak thoracic spine and lumbar A/P shear forces were the least in comparison with the other two anthropometric cases (Figure 8). For all cases the peak thoracic and lumbar spine A/P shear forces were equal.

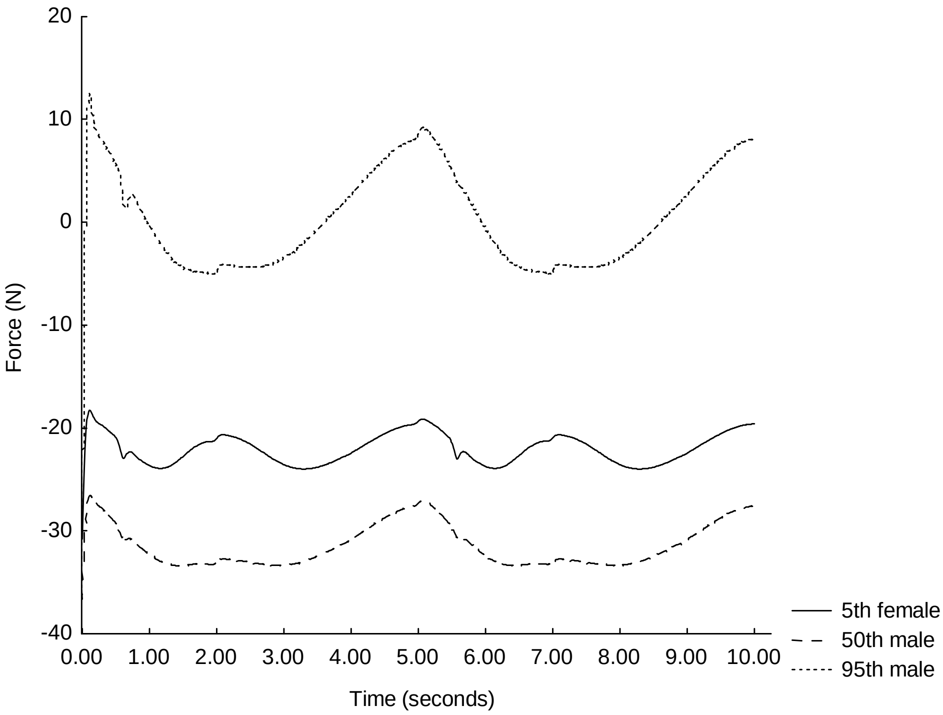

Figure 8. Lumbar spine anterior/posterior (A/P) shear forces (N) for the 3 anthropometric cases (2 repetitions).

Table VII. Thoracic and lumbar spine joint anterior/posterior (A/P) shear forces (N) for the 3 anthropometric cases. Note: positive values indicate forces in a posterior direction and negative values indicate forces in an anterior direction.

Musculoskeletal model	Spinal joint	Mean (N)	Min.	Max.
5th percentile female	Thoracic spine	-22.0	-30.8	-18.3
	Lumbar spine	-22.0	-30.8	-18.3
50th percentile male	Thoracic spine	-31.4	-36.6	-26.5
	Lumbar spine	-31.4	-36.6	-26.5
95th percentile male	Thoracic spine	0.4	-36.2	-12.4
	Lumbar spine	0.4	-36.2	-12.4

The results for wrist and elbow joint A/P shear forces are presented in Table VIII. Peak wrist and elbow joint A/P shear forces were lowest for the 50th percentile male and highest for the 95th percentile male (Figure 9). Peak wrist A/P shear forces were slightly lower than elbow shear forces for all the anthropometric cases.

Table VIII. Right wrist and elbow joint anterior/posterior (A/P) shear forces (N) for the 3 anthropometric cases. Note: positive values indicate forces in a posterior direction and negative values indicate forces in an anterior direction.

Musculoskeletal model	Joint	Mean (N)	Min.	Max.
5th percentile female	Wrist	42.0	16.3	55.7
	Elbow	41.9	10.3	56.6
50th percentile male	Wrist	29.7	16.6	42.8
	Elbow	29.7	10.2	43.8
95th percentile male	Wrist	103.6	31.7	122.4
	Elbow	103.5	18.7	124.1

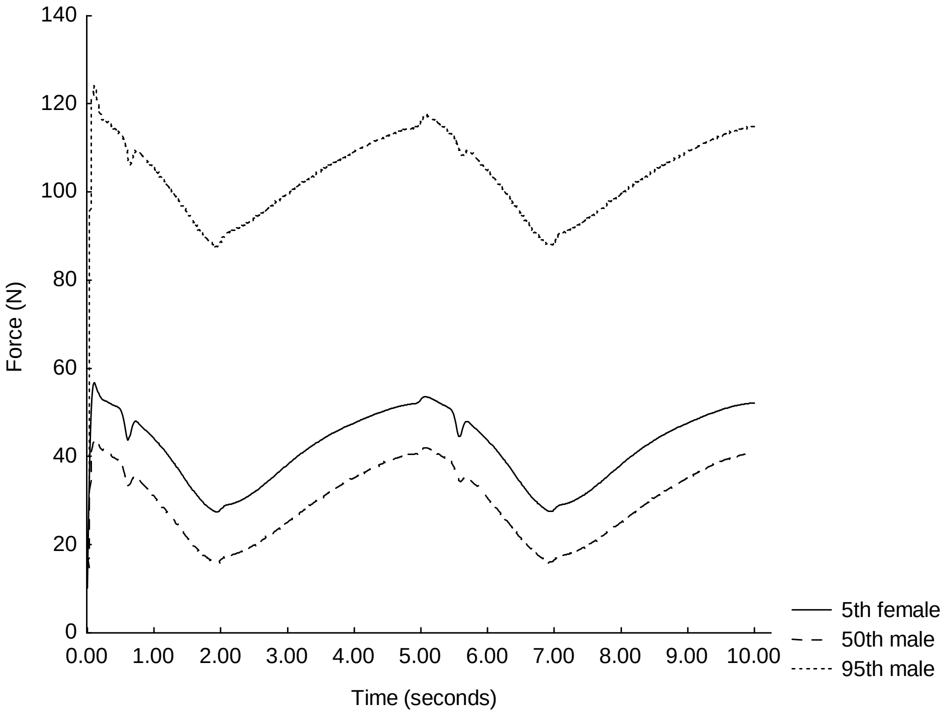

Figure 9. Right elbow anterior/posterior (A/P) shear forces (N) for the 3 anthropometric cases (2 repetitions).

Discussion

Firstly, it can be concluded from this study that the LifeModeler™ default model was not adequate to solve the forward dynamics simulations for any of the anthropometric cases. For the evaluation of the seated biceps curl exercise (first article in the series) the forward dynamics simulations could also only be solved after a number of adjustments had been made to the model such as increasing pCSA of the muscles, manipulating muscle origins and insertions as well as decreasing the joint stiffness in the forwards dynamics simulations. All of these adjustments were implemented in order to solve the simulation without any success. Possible reasons for this could include the degrees of freedom involved in a multi joint exercise involving highly mobile joints such as the shoulder. Furthermore it could be that additional musculature is required to provide more stability in the shoulder joint during the forward dynamics simulations. In this study in order to solve this problem the joint angulations recordings in the inverse dynamics simulations were used to solve the forward dynamics simulations. This option creates a trained PID-servo type controller on the joint axis. The joint is commanded to track an angular history spline with a user-specified gain on the error between the actual angle and the commanded error. A user-specified derivative gain is specified to control the derivative of the error. Therefore, results for muscle forces (N) and contractions (shortening and lengthening) (mm) could not be analysed. Ideally these parameters should be analysed when evaluating an exercise. It appears that more complex, multi-joint or compound exercises that require too many degrees of freedom pose a problem for the default model and therefore models with more detailed musculature may be required to solve the forward dynamics simulations sufficiently. Important musculature required for the performance of the seated row exercise that are not included in the LifeModelerTM default model are the Rhomboideus major and minor and the Rotator cuff group (Supraspinatus, Infraspinatus, Teres minor and Subscapularis). It was not however within the scope of this study to produce anatomical detailed models but rather to evaluate the default model of the software.

Secondly, the study did not indicate any obvious anthropometric differences with regards to the seated row machine’s engineered or manufactured adjustability. All three anthropometric cases appeared to be positioned adequately on the seated row machine. This was not the case with the modelling performed on the seated biceps curl and abdominal crunch machines, which demonstrated the inability of the machines to adjust appropriately to individuals with small anthropometric dimensions such as some females and children. As a result the exercise technique of the 5th percentile female was negatively influenced and injury risk was increased for these exercises.

Lastly, with regards to the biomechanical evaluation in terms of exercise efficacy and injury risk the following could be deduced from the study. Due to the fact that the forward dynamics simulations for this study was solved by recording the joint angulations changes during the inverse dynamics simulations and not muscle length changes, results for the muscle forces and contractions were not obtained and therefore could not be analysed. This negatively influenced the value of modelling with regards to evaluating the seated row exercise as muscle forces and contractions provide important information regarding the efficacy and injury risk of the exercise.

Maximal joint torque values obtained for the wrist, elbow and shoulder appear to be plausible when comparing the values to peak values obtained by means of isokinetic testing at 60 degrees per second. For example wrist flexion/extension values of 13.8 Nm and 12.7 Nm respectively in non-disabled subjects (Van Swearingen, 1983). Elbow flexion/extension values of 36 Nm for both elbow flexion and extension in female college basketball players (Berg *et al.,* 1985) and shoulder flexion/extension values of 77 Nm and 53 Nm for males and 38 Nm and 24 Nm for females respectively in a group of non-disabled (Nicholas *et al*., 1989). Joint torque values for the three joints evaluated were much lower than values obtained during peak isokinetic testing however it is important to bear in mind that the values obtained in this study were not obtained from maximal testing as with the isokinetic testing. The peak elbow joint torque was the highest recorded value for all the joints in the three anthropometric cases which was too be expected as the elbow joint is most involved in the seated row movement.

Not surprisingly, the joint range of motion (wrist, elbow and shoulder) used during the seated row exerciser was smallest for the 5th percentile female and greatest for the 95th percentile male. With the exception of the elbow joint range of motion which was greatest for the 50th percentile male. It is not only important that correct technique be used for resistance exercises such as the seated row exercise but also that exercisers are performed through the full range of motion in order to decrease the likely of injury as well as get the maximum benefits of the exercise. It therefore appears that the three anthropometric models performed the seated row exercise through the full range of motion.

Pushing and pulling as opposed to lifting activities might also be associated with significant risk to the low back (National Institute for Occupational Safety and Health, 1997, Hoozemans *et al.,* 1988). The seated row exercise can be considered a pulling activity. It must be kept in mind that the cited research is primarily referring to occupational tasks however important similarities and conclusions can be drawn with exercises that use similar actions to occupational tasks and activities that require pulling. Furthermore, the spine of the default model does not consist of all the individual vertebrae but rather of various segments that represent the different regions of the vertebral column with joints between these segments. Individualised vertebra and corresponding joints might produce different results.

In 2009 a study by Knapik and Marras (2009) found that there was greater compressive loading at all spine levels when performing pulling compared with pushing activities. Therefore, an individual performing a pulling exercise such as the seated row might be at more risk of a back injury as opposed to individuals performing a pushing exercise such as bench press specifically with regards to compressive loading.

Previous research from the American National Institute for Occupational Safety and Health (NIOSH) recommends that spinal compression forces should not exceed 3.4 kN to avoid injury. However there is a very real threat of musculoskeletal injury before this failure limit value has been reached (Snook and Ciriello, 1991; Cooper and Ghassemieh, 2007, Knapik and Marras, 2009). British standards (BS EN 1005-3, 2002) recommend 600 N as the cut-off point for carrying masses, no further recommendations except " time of exposure needs to be minimised" and "a preferred system requires optimal ergonomic position with reduced back bending posture" are made. Therefore, all three anthropometric cases were well below the recommended failure limit of 3.4 kN. None of the anthropometric cases' peak thoracic or lumbar compression forces were even near the recommended 600 N cut-off and therefore it may be postulated that all things considered the seated row exercise does not appear to cause excessive spinal compression forces that may put the individual at risk for an injury.

Historically, spine compression in the lower lumbar spine has been the variable of interest for risk to the low back during work and exercise training. However, during horizontal force application (pulling of the seated row exercise), it is expected that shear forces within the spine increase dramatically due to the application of force in the hands and the reaction of the trunk musculature. Thus shear forces may represent the critical measure of risk (Knapik and Marras, 2009). According to Knapik and Marras (2009), in general, pushing activities impose greater potentially risky A/P shear forces upon the spine than pulling. Pushing imposed up to 23% greater A/P shear forces compared to pulling. Increases in shear forces were a result of the increased flexor muscle coactivity required for the activity.

Although the spine A/P shear forces recorded were greater than the compression forces, the thoracic and lumbar spine joint A/P shear forces for the three anthropometric cases are also below the most commonly cited spine tolerance of 1000 N for shear force as stipulated by McGill (1996). It is important to note that even if the spine compression and A/P shear forces recorded were well within the acceptable limits the modelling does not take into account the repetitive nature and accumulative effect of exercise. Furthermore, the resistance used was only 50% of each of the anthropometric cases' estimated 1RM and therefore if exercises use a resistance closer to their maximum the loading values may exceed the acceptable limits.

Handle height appears to affect the mechanical load at the low back and shoulder considerably and it is recommended that carts be designed and adjustable so that it is possible to push or pull at shoulder height (Hoozemans *et al.,* 2004). The same principle can be applied to the seated row machine and the handle bars should be at approximately shoulder height, which was the case for the three anthropometric models and thus this could have assisted in reducing the spine loads, especially the A/P shear spine forces. Unfortunately, after conducting a literature search it became clear that information regarding A/P shear forces of the shoulder, elbow and wrist joints is scarce. However, the following information regarding handle height may be applicable in terms of reducing A/P shear forces on these joints during the seated row exercise. Handle height and the magnitude of force were found to be significantly related to the net moment at the shoulder. Net moments at the shoulder are kept low during pushing and pulling activities by keeping the wrist, elbow, and shoulder close to the line of action of the exerted force or by directing the exerted force such that the shoulder joint remains close to the line of action of the exerted force (Hoozemans *et al.,* 1998). Thus, if the handle bars of the seated row resistance training machine are designed in such a way as to ensure correct alignment of the shoulder, elbow and wrist joints, it may assist in reducing the strain that these joints experience during this exercise, especially if a heavy resistance is used.

Conclusion

The limitations using the default model of the software was highlighted. Adjustments had to be made to the default model in order to solve the forward dynamics simulations using recorded joint angulations during the inverse dynamics simulations. As a result no muscle (force and contraction) results could be obtained which negatively impacted the value of the modelling in evaluating the seated row exercise. The anthropometric dimensions of the end-users appeared to be adequately accommodated by the seated row's engineered or manufactured adjustability. Although pulling activities can pose a potential risk for spine injuries it did not appear as if the exercise put undue strain on the spinal structures when exercised with correct positioning and technique at an appropriate resistance.

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