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Validation of a Musculoskeletal Model of Lifting and its Application for Biomechanical Evaluation of Lifting Techniques

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ABSTRACT

Background: Strategies of lifting, including stance width and techniques have significant effects on spine loading and stability. Previous studies examined the influence of them on muscular and postural response. However it is not clear how the impact of stance width on human musculoskeletal might vary according to the chosen lifting technique, so we verified this in our study.

Methods: The present biomechanical study was carried out in 2011. In this study, a whole body musculoskeletal model of lifting was built and validated by experimental data in order to evaluate stance width conditions impact on muscle activation patterns and spine loading during each lifting techniques. Narrow, normal and wide stance conditions were investigated in squat, stoop and semi-squat lifting techniques.

Results: The model muscle's activities were validated by comparing with the experimental muscle activities which resulted in Pearson's coefficients of greater than 0.8. Results indicate significant effect of stance width on muscle activities and joint forces of lower extremity which is dependent on the used lifting techniques. For instance, the anterior posterior force of knee has been affected by stand width in squat more than stoop.

Conclusions: Stance width conditions in each lifting technique exhibit positive and negative aspects and therefore, neither of them can be recommended as the as the perfect technique in terms of biomechanical parameters.

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Introduction

Back pain and disorders of the lumbar disease are known as epidemic to considerable part of people and a common symptom-related reason to see a physician[1]. Furthermore low back pain (LBP) total direct and indirect costs of treatment are very high [2]. Mentioned problems and musculoskeletal injuries associated with the low back disorders (LBD) in the workplaces [3] provide a focus for preventive strategies (including the use of the squat lifting technique and performance of the lift with a wide stance) during lifting as it was demonstrated by previous studies that lifting plays a significant role in causing LBD and LBP [4,5]. Biomechanical evaluation of these lifting strategies could reveal influence of them on lifting performance, and in turn develop the preventive strategies.

Impracticability of direct measurements of muscle forces, problems and costs associated with laboratory methods to measure muscle activity directly have developed biomechanical models[6]. In general, the goal of musculoskeletal modeling and simulation is to predict muscle forces, joint reaction forces or other biomechanical parameters. Recently some studies [7-9] used musculoskeletal modeling system software to build a part of body model and validate it for biomechanical analysis; Dubowsky et al. [8] built and validated a shoulder model for wheelchair (WC) propulsion to investigate the possible link between WC use and shoulder pain.

Lifting techniques is a major determinant factor of mechanical spinal loading during lifting or performing a material handling task[10] and due to the importance of a physically healthy lifting, their effect on musculoskeletal health was widely discussed[11-13]. Lifting strategies including stance width (defined as the distance between the feet in the medial-lateral direction with sagittal symmetry of stance) and lifting techniques (stoop or squat and semi squat) can have a significant impact on spine loading and stability during lifting[14, 15]. Previous studies investigated lifting techniques (stoop and squat) in biomechanical terms to provide some intervention strategies and identify the correct lifting technique [12, 13]. The effect of stance width on lifting has been studied as well, suggesting the use of a wide stance to decrease load on the spine[14, 16]. However, to what extent stance width can affect muscular response and joint reaction forces and how this relies on lifting techniques is rather questionable. Further investigation into these factors and their influence in each other's contribution in lifting performance can be carried out with the aid of a computational model which allows the quantification of muscles activities, lumber, lower and upper extremities forces.

The main objective of this study was to present and validate a rigid-body musculoskeletal model of human body for this purpose.

Methods

Model description

The study was performed in 2011 in the Sahand University of Technology, Tabriz, Iran as a part of a master's thesis. The present model of the lifting was built in the AnyBody Modeling System[17] (AnyBody Technology A/S, Aalborg, Denmark), which is software for development and analysis of multibody dynamics models, particularly models of the musculoskeletal system. AnyBody modeling system is a software package which consists of inverse dynamic and optimization process to determine internal forces by solving the problem of muscle redundancy[17]. This software worked in a text-based, object oriented language named AnyScript. Internal forces including muscle and joint forces have been computed by inverse dynamics in which external loads on the model and segment trajectories used as input. However, for calculating muscle forces, inverse dynamics is not sufficient because of redundancy problem which made muscles statically indeterminate. Optimization combined with inverse dynamics to solve the problem, assuming that the muscles are recruited in an optimal way.

As all parts of the body contribute to lifting, a comprehensive investigation of lifting required a complete model of the human body during lifting. Standing model was used as the base model which is in three main parts, the arms, trunk and leg. The arm part or shoulder area had two sides and each side includes 118 muscles. It was created based on a shoulder Dutch design. The trunk part consists of seven areas including pelvic, lumbar, five thoracic vertebras and chest. Spherical joints between the vertebrae had three degrees of freedom and the trunk part had a total of 158 muscles. The leg part includes bones of the pelvis, thigh, ankle and lower leg muscles which in each side has 35 muscles. Rigid body is composed of 55 pieces in total.

Trajectories have been defined to create movement in the model[17]. Sagittal lifting is simulated by these input data: elbow, ankle, knee, hip and shoulder flexion and trunk extension. Lee et al. [18] captured these joint trajectories in order to find postural respond of body to stable and unstable load during lifting. Xiang et al. [19] simulated human motion during various lifting techniques. The position data has been recorded during both stoop and squat lifting by Lee et al. [18] study used to drive lifting model. Semi-squat simulation model lifting was driven by joint motion captured by Xiang et al. [19] (Figure 1). All joint positions were sampled using a two-dimensional motion analysis system.

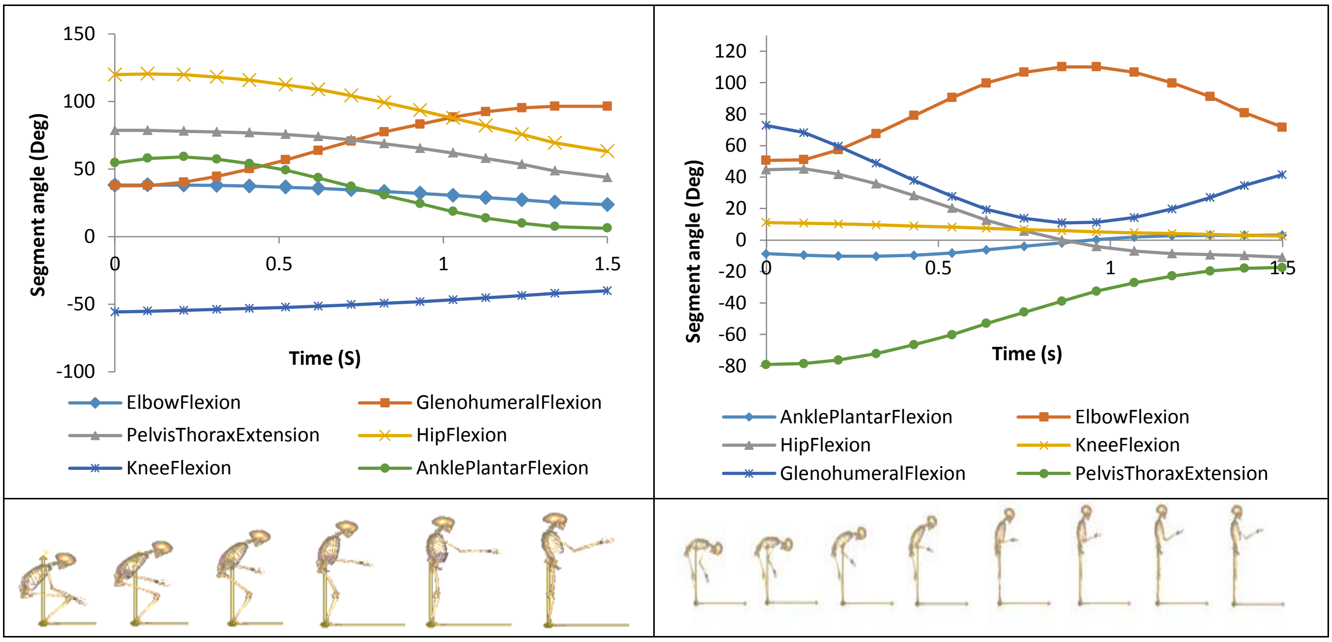

Figure 1: Segment angles respect as a function of time during squat (a) and stoop (b) lifting trajectory captured by lee and Xiang [18, 19]

The toes and heels are fixed to the ground using kinematical condition and to create non-sticking boundary conditions in the model, non-rigid elements used between the feet and the floor. The weight of the lifted load simulated by creating forces concentrated in the centre of left and right hand (palm joint) using 44 Newton force on each hand. Holding of an object is simulated exactly like lifting model and all the segment of body has been fixed.

Anybody modeling system uses inverse dynamic analysis for determining muscle activity to balance given external loads. The equilibrium equation for a musculoskeletal system organizes as the following term[20]:

$$[C]_{i\times m}[f]_{m\times 1}=[r]_{i\times 1} \qquad (1)$$

Where f is a vector of muscle and joint force (internal forces), r is a vector representing the external forces and inertia forces, and **C** is a matrix of equation coefficients. Then for solving redundancy of the muscle recruitment problem, formulate the choosing solutions method as an optimization problem in the following form:

$$\text{Minimize } G(f^{(m)})\ f^{(m)}>0,\ \ i=1..n^{(m)} \qquad (2)$$

Subject to Cf=r

Where the G is the objective function which aimed to optimize internal forces by distributing external forces within them.Various types of functions are available in the software and two of them have been used in the current model; min/max and polynomial. Min/max optimizer minimized the maximum muscles forces and it means that all the muscles can be able of balancing of the external load with a positive distribution and also working together that provides minimal max activity for each of them. Polynomial muscle recruitment is a high order objective function for distributing load evenly between muscles.

Validation methods

Anthropometric parameters were scaled by lee [18] and Xiang[19] participants' data. Lee et al. [18] recorded simultaneously four muscles electromyography (EMG) during both squat and stoop lifting; Biceps (Bi -E), Brachioradialis (Br-E), Erector Spine (Es-E), Hamstring (Ha-E) muscles. More information about the experimental procedure of EMG sampling was provided by Lee et al. [18]. Muscles activities which were computed by software are statistically compared with the captured muscles electromyogram by calculating their Pearson Correlation coefficient (PCC).

Lifting techniques investigation

The presented musculoskeletal model of lifting is validated for 3 kind of lifting technique; stoop, squat and semi-squat. Stance width conditions which have been examined are narrow, normal and wide stances in which hip abduction angle is 5º, 10º and15º, respectively. It was hypothesized that the joint trajectories of body would not change by varying the stance width conditions. All available muscle activates provided by software in each single level and also all Joint reaction forces in three directions of Medial lateral (ML), Proximal Distal (PD) and Anterior Posterior (AP) has been considered in lifting technique investigation.

Results

Table 1 shows the Pearson Correlation coefficients (PCC) among EMGs and muscle activities which have been calculated using two recruitment functions; polynomial and Min/Max during squat and stoop lifting. Using polynomial requirement function lifting, PCCs were greater than 0.72 in squat lifting, which on average was about 0.81. The average PCC during stoop lifting were 0.75 and 0.48 for polynomial and min/max, respectively. The average PCC over all muscles and techniques was about 0.66. On average, the lowest PCC was found in the Bicep (Stoop, Min/max), while the highest was found in the Erector spine (Squat, Polynomial).

Table 1: Pearson's coefficient between lee study muscle electromyography and Muscular activities of model

	Muscles			
Recruit Function	**Bicep**	**Brach**	**ES L3**	**Hams**
Squat				
Poly	0.72	0.83	0.92	0.78
Min/Max	0.42	0.87	0.90	0.28
Stoop				
Poly	0.87	0.30	0.60	0.78
Min/Max	0.10	0.15	0.90	0.76
Semi-squat				
Poly	0.64	0.40	0.81	0.62
Min/Max	0.31	0.32	0.78	0.68

Figure 2 depicts EMGs (recorded during squat lifting by lee) comparing to muscles activities of model. During squat lifting, least consistent between model activities and EMGs is for Biceps by a PCC of 0.72. Figure 2-a showed their poor correlation. However, as it can be seen in the Figure 2-b, brachialis model activity and EMG trends are more similar resulting in greater PCC, 0.83 (Table 2). ES model activity and EMG pattern demonstrated excellent correlation as specified by a PCC of 0.92. Hamstring demonstrate good correlation which was represented by a PCC of 0.78 (Figure 2-d).

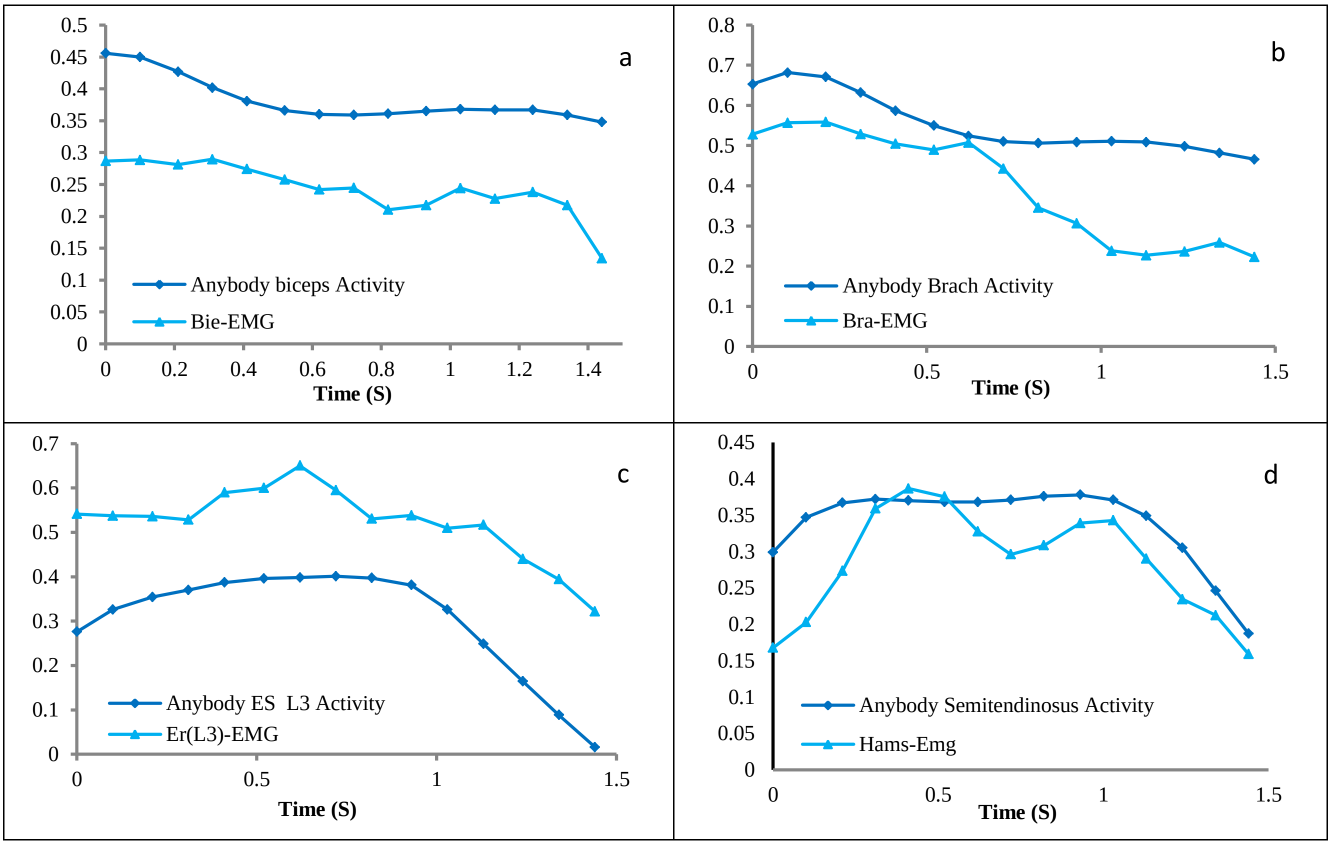

Figure 2: Muscular activities during the lifting time trials calculated by model (using polynomial require function) (Blue line) and electromyography (red line) during squat lifting lee study [18] muscles of Biceps (a) Brachialis (b) Erector Spine (c) and hamstring (d)

Table 2 summarizes the muscle activities for each stance width during holding .Largest per cent muscles activity decrease by changing stance condition is about 6% and is a result of G Me (Gluteus Medius) muscle. These changes for other activities are less than 1%.

Table 2: Muscles activities during holding in three kind of stance width

Number of hips	Tibias anterior	Semitendinosus	Bicep femoris	Gluteus medius
5 hips	0.133	0.192	0.220	0.152
10 hips	0.129	0.187	0.218	0.148
15 hips	0.125	0.181	0.215	0.144

Figure 3 shows muscle activities for each stance width during stoop lifting. *P*-values of paired *t*-test in Table 3 demonstrated that there was no significant different between stance widths for Gluteus Medius muscle activity (*P*>0.050). During stoop lifting technique, TA (Tibialis Anterior) and EDL (Extensor Digitorum Longus) muscle activities patterns are similar and both muscle activities significantly decrease by increasing stance width (Figure 3 a,d). EDL peak activation decreased about 66 per cent by changing the stance width condition from narrow to wide, same as TA muscle. Soleus muscles are more activated during wide stance (Figure 3 b,c). Twenty eight per cent increase in peak activation of soleus activity has been seen in wide stance while rise in G Me muscle's peak activation was 8 percent more.

Figure 4 demonstrates squat lifting muscles activities in three kinds of stance width conditions. During squat lifting, Soleus and Gluteus Medius activities increased with higher hip abduction angle (Figure 4 a, b). In addition, Soleus activity approximately remained unchanged during initial and last periods of lifting span.

Table 3: Paired Samples Test in stoop and squat lifting muscles activities: pair 1 (5-10 hip abduction), pair 2 (5-15 hip abduction), and pair 3 (10-15 hip abduction)

Hip abduction	Gluteus medius			Tibia anterior			Soleus		
	Pair 1	Pair 2	Pair 3	Pair 1	Pair 2	Pair 3	Pair 1	Pair 2	Pair 3
Stoop	0.104	0.062	0.097	0.004	0.005	0.007	0.001	0.001	0.001
Squat	0.001	0.001	0.001	0.117	0.108	0.101	0.001	0.001	0.001

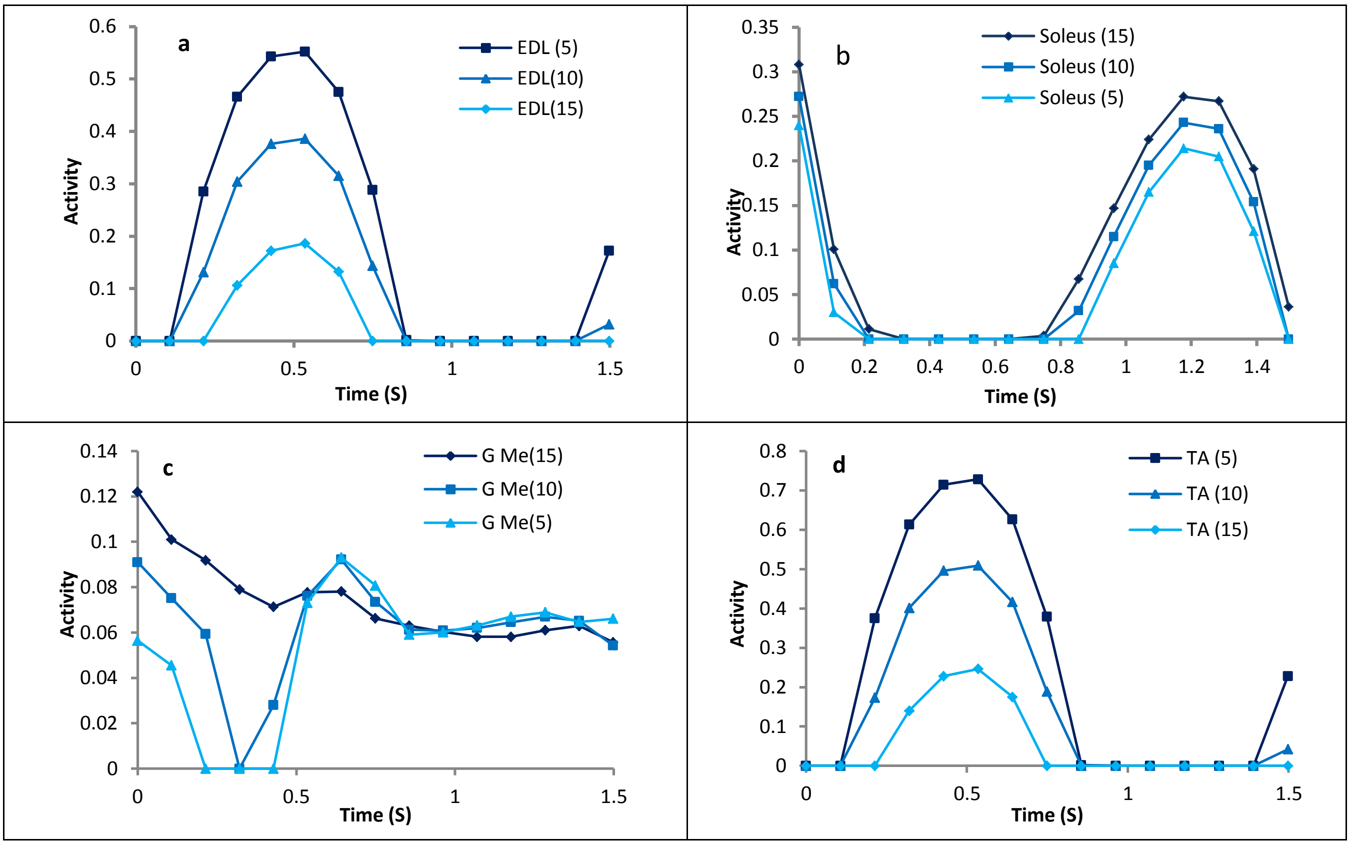

Figure 3: Muscles activities of Extensor Digitorum Longus (a) Soleus (b) Gleuteus medius (c) Tibias anterior (d) during lifting periods in narrow (5), normal (10) and wide (15) stance width, Stoop Lifting

Joint forces

Lower extremity joint reaction average forces has changed as a function of stance width which are showed for holding, stoop, squat and semi-squat lifting in term of per cent change (Figure 5).As it was summarized in Table 4, there were no significant differences (*P*>0.050) between narrow (5 hip abduction) and wide (15 hip abduction) stances for ML, AP hip forces during both squat and stoop , AP knee and PD ankle forces of squat and ML knee and ML ankle forces of stoop. Ankle PD force during stoop lifting increases mostly with increasing stance width, however knee ML force also shows an approximately high value of increase (19%). Using stoop and squat lifting techniques leads to relatively moderate changes in knee and hip PD forces whereas these forces and also ankle PD force remained almost constant during holding

(Figure 5). The largest decrease of the joint force was found in ankle AP force which is about 18%.

Discussion

Exploring different strategies of lifting, including lifting techniques and stance width and their possible contribution to muscle and joint forces need to be investigated since it contribute to alleviate low back disorders. A comprehensive body model was validated by muscle activities utilizing AnyBody software and was used to compare different stance width conditions during lifting techniques. To validate the model, muscle activities of software were compared with the experimental values .Obtained Pearson values for biceps, brachialis, Erector spine and hamstring muscles respectively are 0.72, 0.83, 0.92 and 0.78. These values provided necessary consistent (Pearson greater than 0.6) between analytical and experimental data using polynomial requirement.

Table 4: Paired Samples Test in stoop and squat lifting joint reaction forces of 5 and 15 hip abduction

	Hip ML	Hip PD	Hip AP	Knee ML	Knee PD	Knee AP	Ankle ML	Ankle PD	Ankle AP
Stoop	0.055	0.001	0.500	0.001	0.001	0.370	0.001	0.859	0.001
Squat	0.406	0.001	0.059	0.096*	0.001	0.003	0.054	0.001	0.002

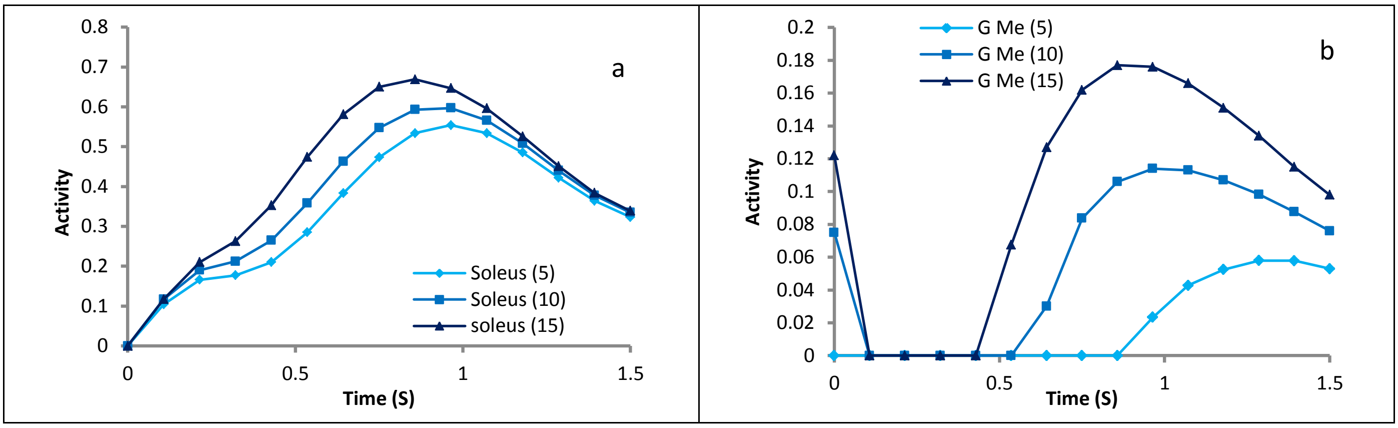

Figure 4: Muscles activities of Soleus (a) Gleuteus medius (b) during lifting periods in narrow (5), normal (10) and wide (15) stance width, Squat Lifting

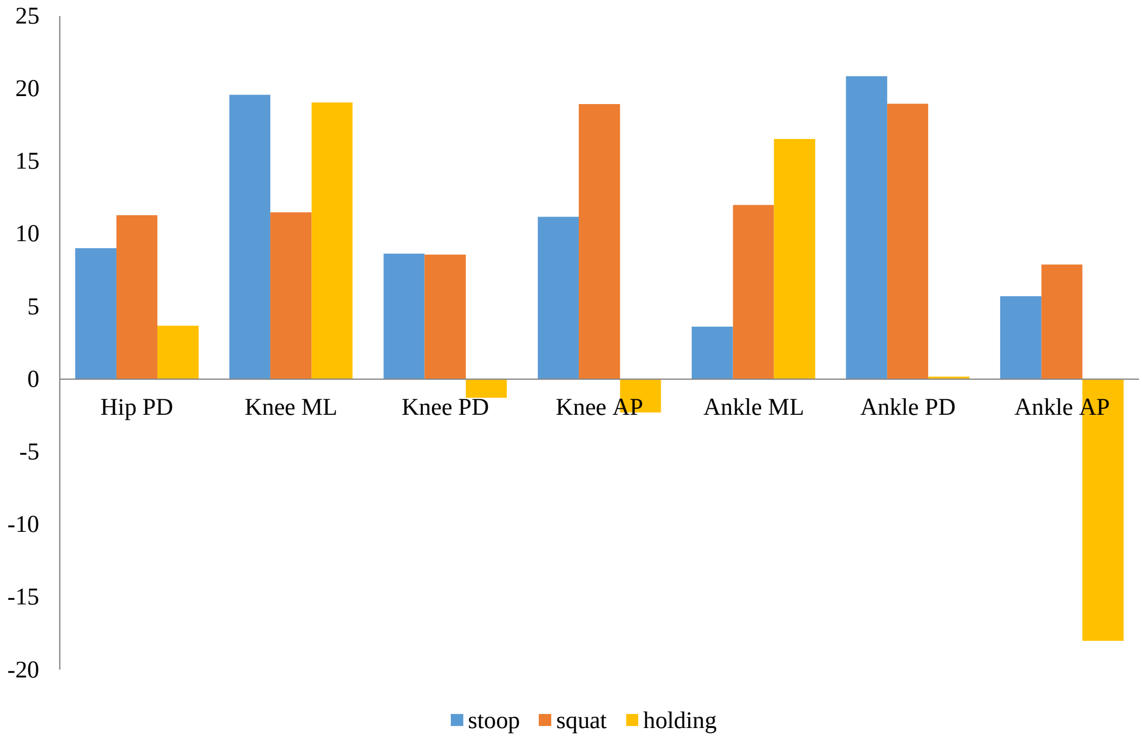

Figure 5: Joint reaction Medial lateral (ML), Proximal distal (PD), and Anterior posterior (AP) force present changes during Stoop and squat lifting and holding in narrow (5), normal (10) and wide (15) stance width conditions

Polynomial muscle requirement result in activities that are more in accordance with experimental data is higher rather than min/max (Table 1). Although some previous studies used min/max requirement considering it as being more reliable optimizer [7, 8] but it have been recommended by Anybody tutorial [20] that using this min/max requirement can produce unrealistic results.

Stance widths do not have any significant effect on trunk and upper body muscles activities in none of the lifting techniques. Results demonstrated that muscles activities of lower extremities had been more affected by changing stance width conditions in the beginning of stoop lifting (between the start times to 0.75 seconds) with respect to its ending period. Unchanged activities in the second half may be due to fixed leg joints. In this period of stoop lifting leg joints angles became almost constant (Figure 3). These results are in accordance to previous study in which Sorensen et al.[16] reported that muscle activation levels were not significantly affected by the stance width during holding.

LDE and TA muscles activity decreased with a similar trend by increasing stance width over stoop lifting period since both muscles have similar function in leg extension. As these muscles are agonists they provide leg extension moment at first half of lifting period and not activated at second half because of leg flexion (Figure 3 b). Therefore, higher peak activation of wider stances shows more required extension moment. Effect of stance width on GMe and Soleus differ in LDE and TA muscles. At the first half period of lifting, lifting up phase, using wider stance caused rise in GMa activity. Effect of stance width on the muscles activities can be identified during squat lifting as well. Similar to stoop lifting, GMe muscle was activated more under a wider stance condition at the beginning of squat lifting but subsequently the activation level decreased.

Some of the joint reaction forces do not significantly influenced by lifting technique. Maximum changes of hand and trunk joint forces were less than 1% while the stance condition was altered from narrow to wide. Wide stance increased each joint average reaction force during both stoop and squat and since the compressive forces (proximal) of joints were greater than the shear forces, influence of stance width on proximal forces were more than shear forces. Percentage increase in lower extremities forces for stoop and squat lifting are approximately similar except to the hip joint anterior posterior force (Figure 4).

Conclusions

Biomechanical advices often include using wider stances, flexed knees and straightened lumber in order to decrease lumber loading and reduce the risk of injury during lifting. But according to the results, wide stance not only does not consist in spine loading but also it increased the compressive forces of the lower extremities. This conflict may be caused by considering same trajectories for different stance conditions and two dimensional modelling which are the major limitations of the current study. It is recommended that future studies use a three dimensional model of lifting to assess the stance width by implying more realistic trajectories.

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Conflict of interest statement

There is no conflict of interest to be declared.

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