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EFFECTS OF EXTERNAL LOADING ON LUMBAR EXTENSION MOMENT DURING SQUAT LIFTING

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Abstract
Objectives: The main objective of this study has been qualitative investigation of the effects of external loading on the lumbar extension moment during squat lifting. Findings of this study may allow to determine the factor with the most considerable effect on the lumbar extension moment and may help determine the lumbar spine risk factors at temporo-spatial coordination during squat lifting. **Material and Methods:** Twelve healthy men volunteered to perform slow and fast squat lifting of a box of varied mass (4 kg, 8 kg and 12 kg). The eight-channel electromyography was applied to detect the activities of abdominal (*rectus abdominis* and external oblique) and lower back muscles (*iliocostalis lumborum* and *multifidus*). The lumbar extension moment was calculated using 3D linked segment model. Ground reaction forces and kinematic data were recorded using a Vicon system with 2 parallel Kistler force-plates. **Results:** Significant increases (both p-values < 0.05) were detected for the peak lumbar extension moment with increases in the lift speed and box weight. Moreover, a significant interaction ($p = 0$) was detected between the lift speed and box weight. Furthermore, insignificant differences (all p-values > 0.05) were detected between the lumbar angles related to the lower trunk muscles peak activities and lumbar angle related to the peak lumbar extension moment in most of the lifts. **Conclusions:** According to the findings, the inertial force of the lifted box is the most important factor that affects the lumbar extension moment during squat lifting. Moreover, critical lumbar angles are seemingly those ones in which the lifted box reaches the peak acceleration. Int J Occup Med Environ Health 2017;30(4):665–679

Key words:
Electromyography, Squat lifting, L5–S1 joint, Extension moment, Box weight, Lift speed

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INTRODUCTION

Weight handling and lifting task as one of the most applicable and frequent tasks among labor and industrial tasks is a combination of trunk muscles activation including back and abdominal muscles [1–4]. Trunk muscles counteract the shear forces and also provide the trunk extension moment in order to compensate for the imposed bending moment [5,6]. In addition, the lumbosacral (L5–S1) joint in the lumbar zone of the spine is the most critical point that suffers bending moment and is in high risk of injury. Hence, the knowledge of the lumbar spine kinetic patterns is necessary for interpreting the function and strategy of neuromuscular system and furthermore for determining critical lumbar angles which contribute to the risk of injury of the lumbar spine under various task conditions.

During a lifting task, trunk extension moment is affected by many variables such as the weight of lifted load and lift speed. Higher external trunk moments and higher levels of muscle activations have been reported with increase in the weight of the lifted load [7]. Hwang et al. [8] have reported increases in the lumbar extension moment and lower trunk muscle activities with increase in the weight of lifted load. Increased trunk moment has been reported to be related to the increased muscle activation and increased 3 dimensional spinal loads [9–13]. Marras and Mirka [10] have reported increased muscle activation and spinal loads with increase in the trunk velocity. Many researchers have reported the increase in the lift speed increases the muscle activity [10,14], spinal loading [13,15,16] and lower back moments [17–19]. Mawston and Boocock [20] have found that lumbar posture may significantly alter the functional role of the erector spine and resulting lumbar moment when lifting and lowering and has implications for the loads that the spine must contend with. These findings reinforce the alteration of trunk kinetics and kinematics to adjust to changes in the lift speed and weight of lifted load.

Many researchers have investigated trunk kinetics under different task conditions such as isometric and controlled isokinetic conditions [21–23] as well as free-dynamic lifting conditions [8,13,24]. Free-dynamic and unconstrained conditions have been reported to match realistic lifting conditions better than constrained conditions [25].

Knowledge about the effects of task execution variables on the lumbar extension moment (extension moment at the L5–S1 joint) during weight handling and lifting tasks has been always of great importance since it helps clinicians to determine the risk factors and ranges of motion with high risk of injury. Hence, the main objective of this study has been qualitative investigation of the effects of external loading (lifting of different masses at different lift speeds) on the lumbar extension moment during squat lifting. Findings of this study may allow to determine the factor with the most considerable effect on the lumbar extension moment as well may help determine the lumbar spine risk factors at temporo-spatial coordination during squat lifting. As mentioned above, many researchers have investigated the effects of task execution variables on the lumbar extension moment, quantitatively. So, the novelty of this study is the qualitative investigation of lumbar extension moment during squat lifting.

MATERIAL AND METHODS

Subjects

Twelve healthy male subjects volunteered to participate in this study by signing the written consent form (age: 28.5±3.57 years old, weight: 66.62±3.6 kg, height: 170±2.64 cm and body mass index: 23.12±1.65 kg/m^2). The subjects had no history of back musculoskeletal disorders or back pain and had almost the same previous work experiences and demographics, too. The same training sessions were held 4 days before the first testing to make all subjects familiar with the experiments. Since the determined load levels (4 kg, 8 kg and 12 kg box weights) were equal for all subjects in this study, so the criteria for inclusion and exclusion of the subjects were based on the similar body mass indexes (BMIs) and the same previous work experiences among the volunteers. The BMI was so determined to be in a mean level with accordance to the determined load levels. The procedures and ethical principles of this study were done according to the World Medical Association Declaration of Helsinki and were approved by the research ethics committee of the Department of Biomedical Engineering at the Science and Research Branch, Islamic Azad University.

Lifting tasks

Using the symmetric squat technique (lifting with flexed knees), the subjects lifted a box (32 cm (width) × 40 cm (length) × 25 cm (height)) with 2 handles, which was placed symmetrically in front of their feet. The box was lifted to an erect symmetrical standing position (Photo 1). Lifts were performed using 3 masses (4 kg, 8 kg and 12 kg). Moreover, lifts were performed at slow and fast speeds. Lifting at slow speed lasted about 3.3 s and lifting at fast speed lasted about 1.1 s. The speeds were controlled by a metronome. In this study, the box weights were so determined to be almost similar to the load distribution observed in industrial lifting tasks [26]. Furthermore, the lift speeds were so determined to be different so that the effects of lift speed changes may be observed on the lumbar extension moment. Equal degrees for bended lumbar in subjects were adjusted using a goniometer at the start of the lifting. All lifts were repeated twice with a break interval of 2 min. Furthermore, in order to avoid any effects of training (systematic effect) and fatigue, the order of performances was randomized. To ensure the reliability of measurements, the subjects repeated the experiments 1 week after the first testing session.

a) b)

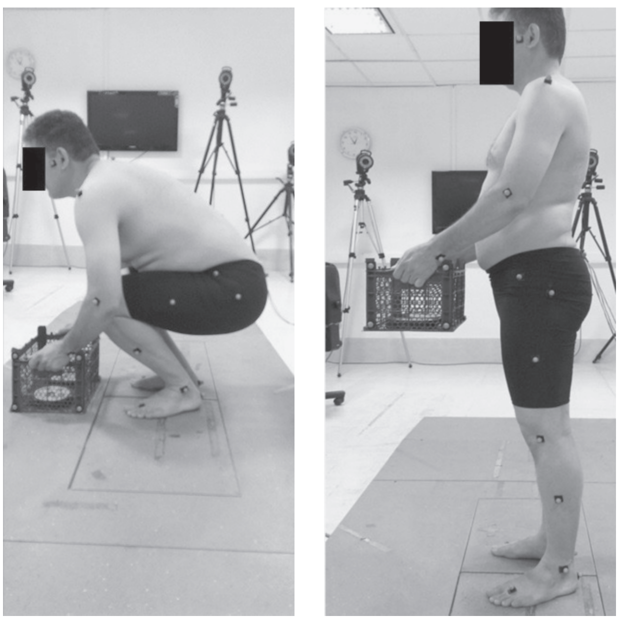


Photo 1. Positions of the body during squat lifting a) at the start of movement and b) at the end of movement

Electromyography

In order to analyze the muscles activity, the eight-channel electromyography (EMG) (Biometric MWX8, UK) of the lower back muscles and abdominal muscles was used. The surface EMG electrodes (bipolar silver–silver with a diameter of 10 mm and an inter-electrode distance of 20 mm) were attached to the shaved and cleaned skin before each experiment. The surface electrodes were placed over 2 pairs of flexors (*rectus abdominis* and external oblique muscle) and 2 pairs of extensors (*iliocostalis lumborum* and *multifidus*). The electrodes were positioned with accordance to the Ng et al. [27] (Photo 2).

The electrodes for external oblique muscle were positioned just below the rib cage, along the line connecting

a) b)

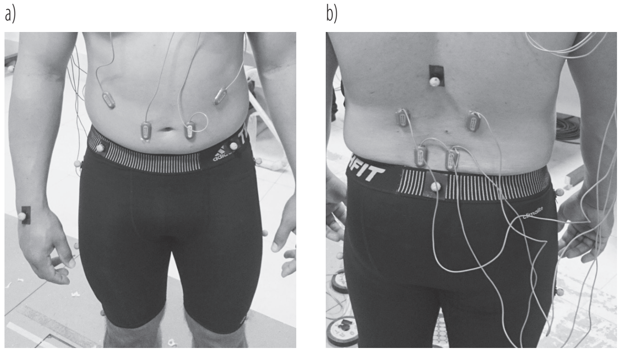


Photo 2. Positions of the surface electrodes a) for abdominal muscles and b) lower back muscles

the most inferior point of the costal margin to the contralateral pubic tubercle. The electrodes for *rectus abdominis* were attached 1 cm above the *umbilicus* and 2 cm lateral to the midline. The electrodes for *iliocostalis lumborum* were attached at the L2 level, parallel to the line connecting the posterior superior iliac spine (PSIS) to the lateral border of the muscle at the 12th rib. The electrodes for *multifidus* were positioned at the L5 level, parallel to the line between PSIS and L1–2 interspinous space [27,28]. The EMG signals of the lower trunk muscles were sampled at 1000 Hz and were band-pass filtered at 10–500 Hz [29] and then rectification and root mean square with a time constant of 20 ms were applied on the EMG signals. The maximum voluntary contraction (MVC) in extension (for back muscles) and the flexion and lateral flexion in both sides (for abdominal muscles) was used in order to normalize the EMG data. The MVCs were measured twice and also were measured for 5 s with a 2-minute break interval between tests. Moreover, the order of contractions was randomized. Before each test, warm-up trials were performed. The subjects made their maximal effort and also avoided any jerky contractions during the MVC tests. The same procedures were carefully reproduced in the next testing session in order to obtain high reliability in measured data.

Motion analysis and kinematic data collection

Using a dynamic 3-dimensional linked segment model, a Vicon system (Vicon-460 Motion System Ltd., LA, USA) and 27 passive reflective markers, the kinematic data were collected at 100 Hz and also the movement patterns and lumbar extension moment were calculated. Markers were attached to the skin (on the right and left sides of the body) according to the Helen Hayes marker set-up [30]. A thirteen-segment model for whole body was used for determining the positions of the following joints: the distal part of the *lateral malleolus* (the ankle joint), the fourth metatarsophalangeal joint, *epicondylus lateralis* (the knee joint), greater trochanter (the hip joint), the L5–S1 joint, the first thoracic vertebra (C7–T1), the ear channel (the head), the glenohumeral joint, the elbow joint (*epicondylus lateralis*) and the wrist joint (ulnar styloid).

The body model was consisting of foots, lower legs, upper legs, pelvis, trunk, head plus neck, upper arms and forearm plus hands. In order to define the movement and location of the box center of mass in sagittal plane, 4 markers were attached to the box. The ground reaction forces were concurrently recorded using 2 parallel force-plates (Kistler 9286AA) and data was stored at 100 Hz after filtering with an analog low-pass filter at a cut-off frequency of 30 Hz. Finally anthropometric data (mass, length, center of mass and moment of inertia of the segments) was measured according to de Looze et al. [31].

Data analysis

The angle between the line through the L5–S1 and T1 and the line through the hip and L5–S1 joints was considered as lumbar angle. The anthropometric data, ground reaction forces and kinematic data were inputted to the linked segment model. Inverse dynamic was applied in this study to calculate the lumbar extension moment for each lift. The "zero" point of time for all lifts was defined using an electrical micro-switch which was placed between the box and ground and was activated as the box left the ground. At the moment that the box was leaving the ground, the height of the box markers began to increase. Therefore, the activation of the electrical micro-switch and increase in the height of box markers in EMG and kinematics data marked the lift start, at which the lumbar angle was approximately 86°, and the lift end at which trunk was completely extended, was defined by constant values for the lumbar angle (approximately 27°).

In order to obtain the maximum amount of normalized EMG values as well as a clear linear envelope curve showing the trend of muscle activity, the calculated root mean square values of the EMG data for each muscle were normalized with respect to the MVC values. In order to obtain the average curve patterns for the lumbar extension moment and EMG activity of muscles in each lift, time normalization was applied to the data. All calculations and data analyses were performed for the lumbar angles between the lumbar angle in which the box left the ground and the lumbar angle in which the trunk was fully extended, in sagittal plane, using MATLAB-R2010 software.

Statistical analysis

In order to test the effects of the box weight and lift speed on the lumbar extension moment, 2-way repeated measure ANOVA was applied to the data. The paired t-test was also applied to test if the lumbar angle related to the peak lumbar extension moment was significantly different from the lumbar angles related to the lower trunk musculature peak activities. P-values lower than 0.05 were considered for significant differences in data. Using intraclass correlation coefficients (ICC), the reliabilities for all measurements were examined [29]. SPSS statistical package (v. 16) was applied for statistical analyses. Interpretation of the ICC was with accordance to Domholdt [32].

RESULTS

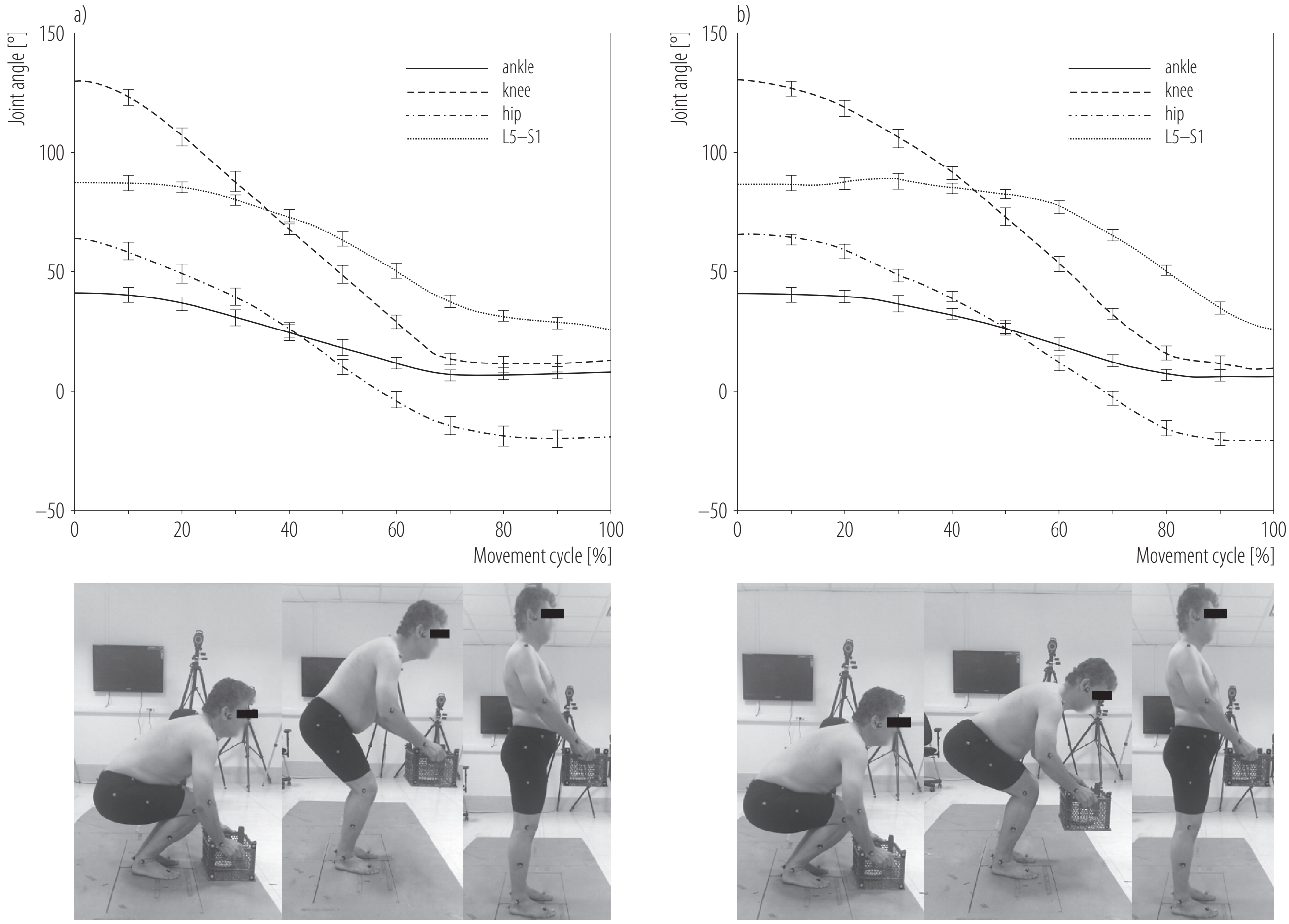
The ICC reliability values for the peak lumbar extension moment, peak EMG activity and angular position of the joints were calculated for each lift. Best reliabilities were resulted for all measurements in the slow speed lifting (0.80 < all ICCs < 0.89) for all box weights. In addition, high reliability was resulted in the fast speed lifting (0.71 < all ICCs < 0.81) for all box weights.

The Figure 1 represents the angular positions for the lower extremity joints. Except for the lumbar joint, almost the same angular position patterns were observed for each joint between the slow lifting and fast lifting. The most changes in the lumbar angle during the fast lifting occurred after approximately 20% of movement time while the most changes during the slow lifting occurred after approximately 50% of movement time. During the slow lifting, the lumbar spine flexed much more after movement start and after that extended till the end of movement, which shows the different movement patterns between the slow lifting and fast lifting because of the different lumbar angular positions.

The Table 1 represents the average peak lumbar extension moment and average peak activity of trunk muscles with the related average lumbar angles for each lift. The results of 2-way repeated measure ANOVA test indicated that there were significant increases (both F-values ≥ 57.125 and both p-values < 0.01) for the peak lumbar extension moment with the increases in the lift speed and box weight. Moreover, a significant interaction (F = 85.322 and p = 0.000) was detected between the lift speed and box weight.

Furthermore, the results of the paired t-test showed insignificant differences (all t-values ≤ –0.33 and all p-values > 0.05) between the lumbar angles related to the trunk extensors peak activities and lumbar angle related to the peak lumbar extension moment, for the fast lifting of all masses. The results for the slow lifting were significant (both t-values ≥ 21.45 and both p-values < 0.05) for 4 kg and 8 kg masses. The results showed significant differences (all t-values ≥ 8.31 and all p-values < 0.05) between the lumbar angles related to the trunk flexors peak activities and lumbar angle related to the peak lumbar extension moment, for the slow lifting of all masses (except for the external oblique in lifting of 4 kg and 8 kg masses) and furthermore insignificant differences (all t-values ≤ –0.12 and all p-values > 0.05) observed for the fast lifting of all masses (except for the external oblique in lifting of 4 kg mass).

The Figures 2, 3 and 4 represent the curve patterns of the lumbar extension moment, linear acceleration of the lifted box and lower trunk musculature activities for different lifts. The curve patterns of the lumbar extension moment seemed to be different at the beginning and



The joint angles were defined as the angle between the line through the upper segment and the line through the lower segment.

Fig. 1. Lower joints angular positions for the lifting at a) fast speed and b) slow speed

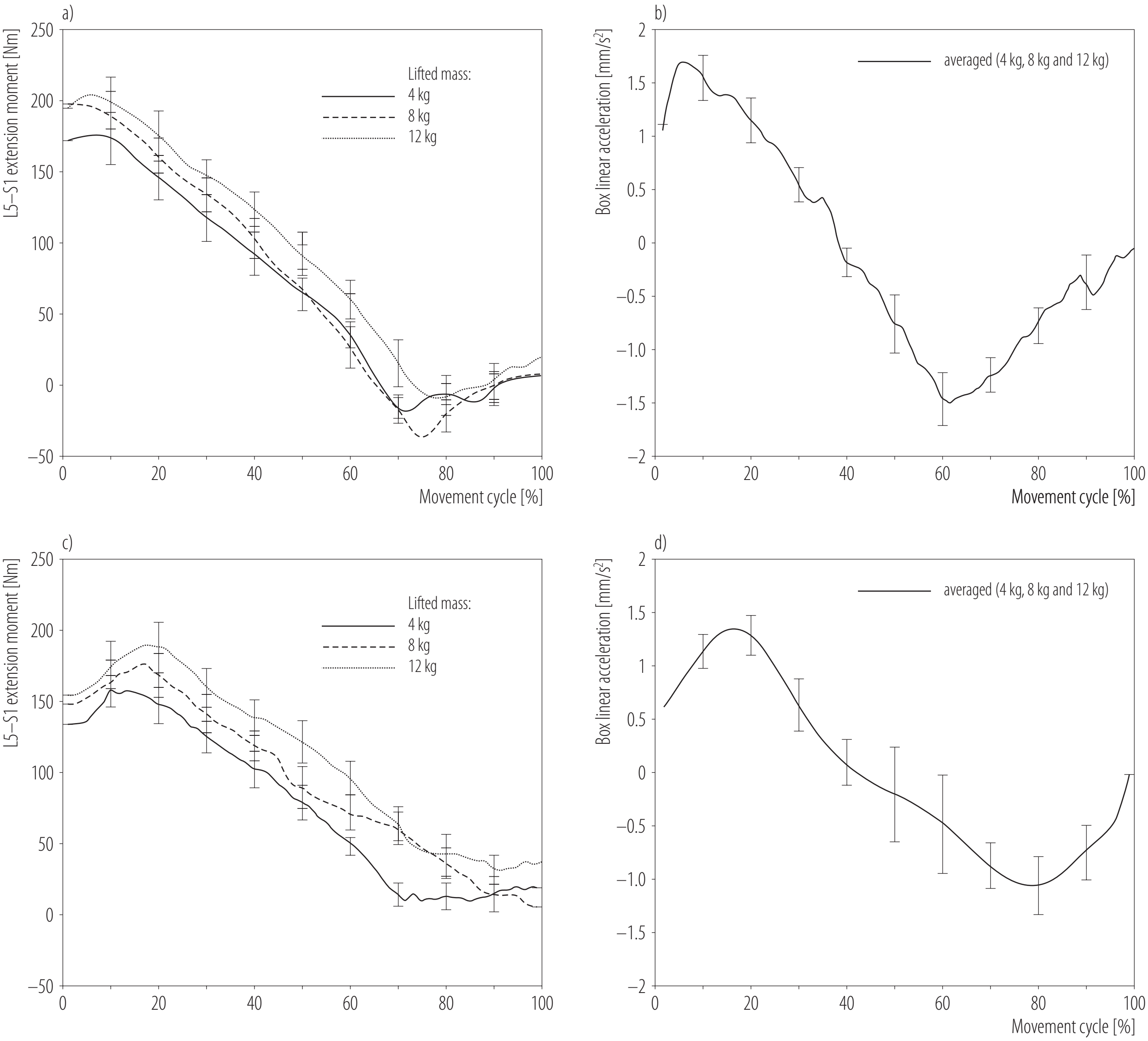
end of the movement between the slow lifting and fast lifting (Figure 2). The extension moment during the fast lifting reached its peak value at the beginning of the movement between the 0% and 5% of the movement time approximately at the lumbar angle of 86° while the extension moment during the slow lifting reached its peak value between 10% and 20% of the movement time approximately at the lumbar angle of 86°. Between 65% and 90% of the movement time, the lumbar extension moment at the fast lifting reached negative values and then moved toward the zero point. During the slow lifting, the extension moment showed a diminishing trend from the peak value toward the zero point. The increase in the box weight didn't seem to change the trend of the extension moment curve pattern significantly at both lift speeds. The same trends as those of the lumbar extension moment curve patterns were observed in the linear acceleration curve patterns of the lifted box center of mass at both lift speeds (Figure 2). This may indicate the dependency of the lumbar extension moment on the inertial force of the lifted box.

External loading had the same effects as those of the lumbar extension moment on the extensors curve patterns at both lift speeds (Figure 3). The increase in the lift speed appeared to raise the muscle activity level of the extensors for all box weights. Moreover, increase in the box weight did not seem to change the trends of the extensors curve

Table 1. Peak extension moment at the L5–S1 joint and lumbar muscles peak activities with the related lumbar angles, for the lifting of 3 different masses at fast and slow speed

Box weight and lift speed	Muscle peak activity [%MVC] (M±SD)				Lumbar angle [°] (M±SD)					L5–S1 peak moment [Nm] (M±SD)
	IL	MU	RA	EO	IL	MU	RA	EO	L5–S1	
4 kg										
slow	27.57±3.12	20.62±3.08	3.97±1.61	4.75±1.87	87.2±1.20	87.2±1.10	87.6±1.31	85.4±0.88	85.7±0.40	159.52±5.78
fast	30.38±3.08	24.09±3.28	4.09±1.77	5.13±1.57	86.6±0.88	86.6±0.76	86.1±0.61	77.2±2.10	86.6±0.76	175.80±5.25
8 kg										
slow	38.66±3.25	26.45±3.11	4.78±1.51	6.78±1.72	87.9±1.28	87.6±1.18	87.1±1.62	86.8±2.08	86.0±0.42	177.80±4.42
fast	37.18±2.98	27.56±2.89	4.61±1.22	4.99±1.64	86.3±0.89	86.5±0.58	86.6±1.05	86.5±1.98	86.1±0.64	197.44±5.29
12 kg										
slow	37.40±3.02	27.48±3.23	4.28±1.57	5.94±1.56	86.0±1.21	86.0±1.02	87.9±2.11	87.2±1.66	86.1±0.55	191.68±5.66
fast	36.35±2.89	28.18±3.37	4.87±2.02	5.14±1.66	86.3±0.49	86.1±0.31	86.8±1.71	86.5±1.81	86.6±0.48	204.29±4.94

MVC – maximum voluntary contraction; M – mean; SD – standard deviation.
IL – *iliocostalis lumborum*; MU – *multifidus*; RA – *rectus abdominis*; EO – external oblique.



The box was lifted from a shelf 10 mm above the ground (approximately at lumbar angle of 86°) to full extension of the trunk.

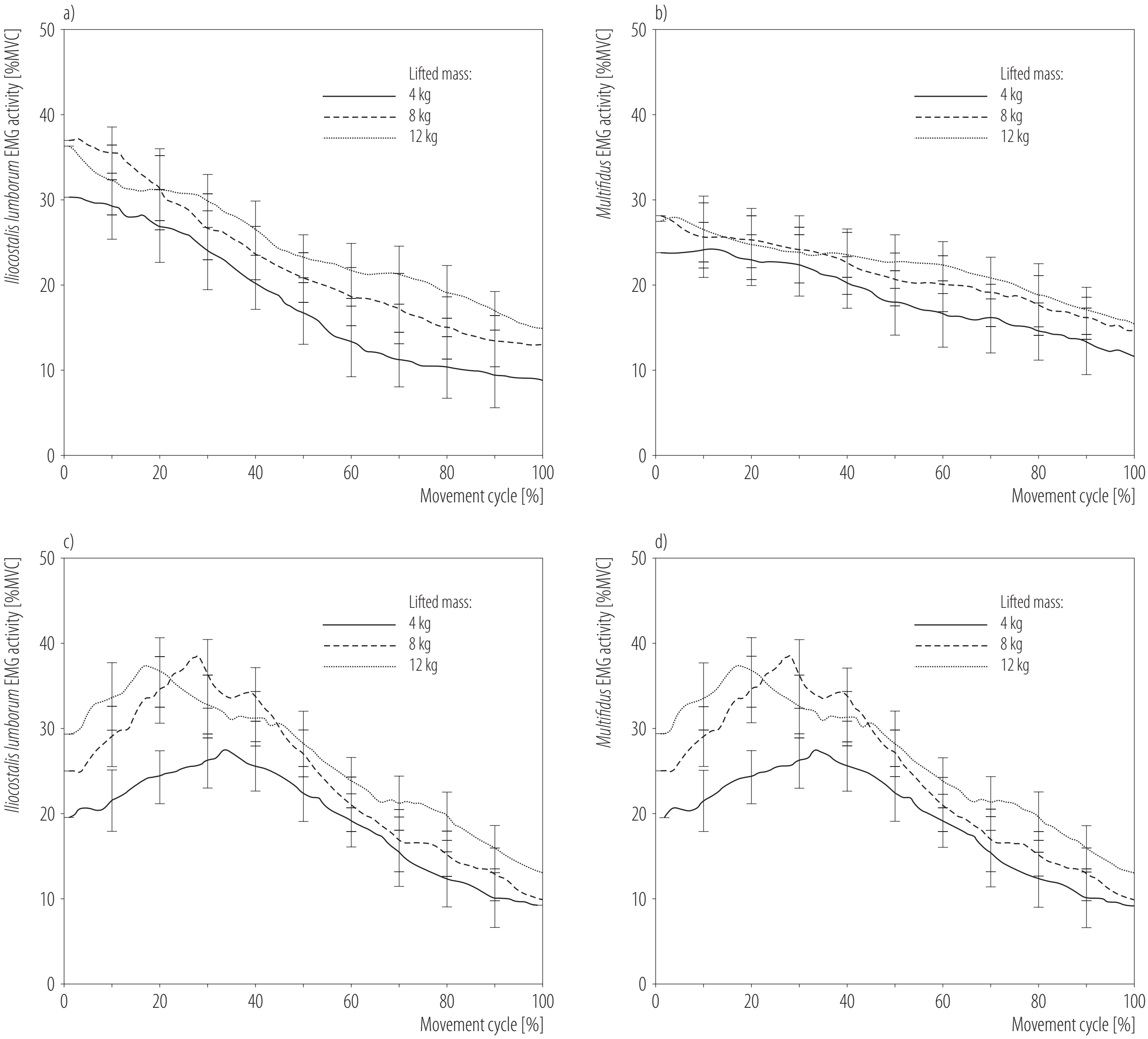
Fig. 2. Extension moment at the L5–S1 joint and linear acceleration of the box center of mass for the lifting of 3 different masses at a), b) fast speed and c), d) slow speed

patterns at both lift speeds. The same curve patterns as those of the extensors were observed in the flexors due to the external loading (Figure 4). Furthermore, increase in the lift speed appeared to raise the muscle activity level of the abdominis rectus. The increase in the box weight didn't seem to change the trends of the flexors curve patterns.

DISCUSSION

Lumbar angular position

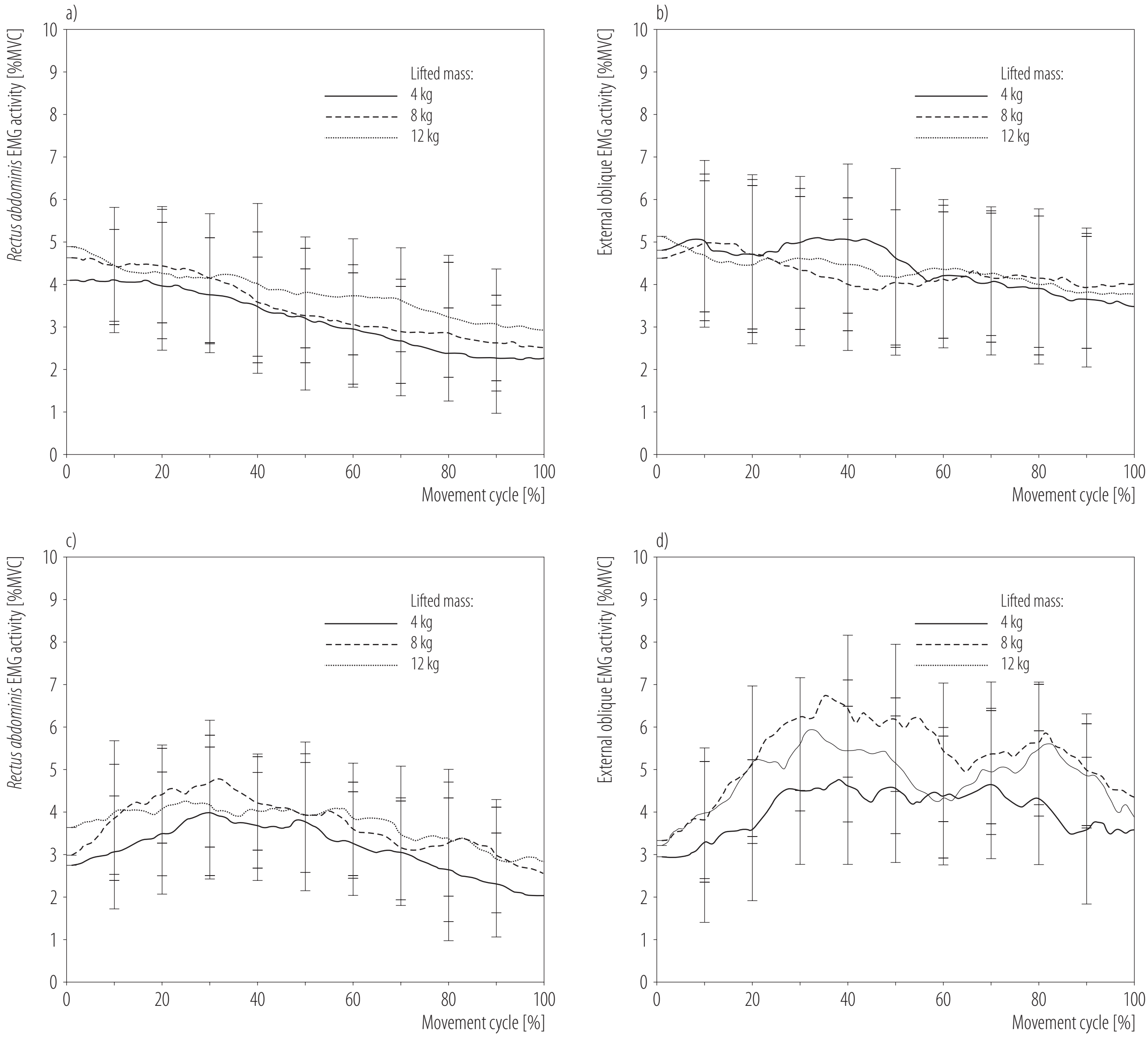
Different movement patterns between the slow lifting and fast lifting (because of the different lumbar angular positions) may refer to compensatory role of the lumbar joint and muscles for the effects of high speed



Each curve is the average curve of a muscle pair. The box was lifted from a shelf 10 mm above the ground (approximately at lumbar angle of 86°) to full extension of the trunk.
MVC – maximum voluntary contraction.

Fig. 3. Electromyography (EMG) of the lower trunk extensors for the lifting of 3 different masses at a), b) fast speed and c), d) slow speed

(imposing excessive forces) during the fast lifting. Fathallah et al. [25] and Rossi et al. [33] reported the compensatory role of the joints and muscles to maintain stability during the execution of different exercises. These findings reinforce the compensatory actions of joints and muscles to get proper stability during a lifting performance. Therefore, due to the different lumbar angular positions between the slow lifting and fast lifting and moreover due to the dependency of lumbar extension moment on the trunk kinematics [7], different curve patterns would be expectable for



Explanations as in Figure 3.

Fig. 4. Electromyography (EMG) of the lower trunk flexors for the lifting of 3 different masses at a), b) fast speed and c), d) slow speed

the lumbar extension moment between the slow lifting and fast lifting. Many researchers have reported that increase in sagittal trunk motion and lift speed influences muscle activity [10,14], therefore, like the lumbar extension moment, different curve patterns would be expectable for the EMG of the lower trunk musculature activities.

Lumbar extension moment

The increase in the peak lumbar extension moment due to the increases in the box weight and lift speed was expectable regarding the findings of previous studies [7,17–19]. The increase in the box weight did not seem to affect the trend of the mentioned curve patterns at both lift speeds and this may be reasonable because of the same lumbar angular positions and same trunk kinematics in lifting of 4 kg, 8 kg and 12 kg box weights at the same lift speeds. The same findings were observed in a previous study [8] for the influence of raising box weight in the curve pattern and peak value of the lumbar extension moment. The main differences in the curve patterns of the lumbar extension moment (between the slow lifting and fast lifting) were observed at the beginning and end of the movement.

As the Figure 2 shows, the linear acceleration of the lifted box followed the same curve trends as those of the lumbar extension moment at both lift speeds. Increase in the lift speed results in higher acceleration and consequently in higher inertial force for the lifted box which implies higher lumbar extension moment [34]. During the fast lifting as seen in the Figure 2, the box left the ground rapidly and this caused the peak extension moment at the beginning of the movement (approximately in the range of 0–5% of the movement time at which the lumbar angle was 86°) whereas during the slow lifting, the box left the ground gradually and then reached the peak acceleration and at the same time the extension moment reached its peak value (approximately in the range of 10–20% of the movement time in which the lumbar angle was 86°). Therefore, the peak extension moment seems to be affected by the peak acceleration of the lifted box. As the Figure 2 shows, the linear acceleration of the lifted box increased in negative direction after almost 40% of the movement time. In this manner, the inertial force of the lifted box gets the same direction as the movement direction and becomes as an aid force so that helps for the trunk extension and this may justify the diminishing trends of the lumbar extension moment at both lift speeds. Although the curve patterns of the lumbar extension moment were different, the lumbar angles of the peak extension moment were the same (86°) at both lift speeds. The reason is that in both slow lifting and fast lifting the lumbar angle was approximately 86° at about 0–20% of the movement time at which the lumbar extension moment reached its peak value before the lumbar extension. Thus, it appears that the lumbar angle does not directly affect the peak lumbar extension moment.

Lumbar extension moment counteracts imposed bending moment which in result is the sum of gravitational forces and inertial forces acting on the subject. Gravitational forces are constant which are dependent on the subject and lifted box masses. Inertial forces are variable which depend on the subject and lifted box masses and their accelerations as a result of motion [34]. Since acceleration is a vector quantity, inertial forces may alter the imposed net force and bending moment and as a result may alter the lumbar extension moment throughout the squat lifting. Furthermore, significant interaction between the lift speed and box weight relating to the peak lumbar extension moment refers to the fact that the relationship between each of these variables and the peak lumbar extension moment depends on the amount of the other variable. Thus, since the inertial force is the product of mass and acceleration of the center of mass, the interaction between the lift speed and box weight may refer to the effect of lifted box inert force on the lumbar extension moment during squat lifting.

As the results showed:

- increase in the box weight raised the peak lumbar extension moment,
- increase in the lift speed raised the peak lumbar extension moment and changed the curve pattern of the lumbar extension moment,
- the linear acceleration of the lifted box appeared to affect the peak lumbar extension moment,
- the interaction between the lift speed and box weight seemed to refer to the effect of lifted box inertial force on the lumbar extension moment.

So, according to these findings inertial force of the lifted box, which is directly related to the weight, speed and linear acceleration of the lifted box, seems to be the main factor that affects the lumbar extension moment.

Muscle activity

Both increases in the box weight and lift speed appeared to increase the muscle activity level in most of trunk muscles (particularly the extensors) which corresponds to the findings of previous studies [9,16,18,19]. As the results showed (Figure 4), the external oblique muscle behaved irregularly with each increase in box weight and lift speed. The reason may be related to the influence of intra-abdominal pressure (IAP) on the abdominal muscles activation [35]. Unlike the external oblique muscle, increased activation levels were observed for *rectus abdominis* muscle with increases in the box weight and lift speed (Figure 4). No conclusive explanation may be given for the alteration of abdominal muscles activation because of the relationship between IAP and abdominal muscles activation.

According to the results (Table 1), the lumbar angles related to the lower trunk muscles peak activities and peak lumbar extension moment were similar in most of the lifts. In addition, almost the same effects on the curve patterns of the lumbar extension moment and muscle activity were observed by raising the box weight and lift speed (Figures 3 and 4). So, this indicates the same effects of the external loading on the lumbar extension moment and muscle activity (particularly the extensors). Regarding these findings and considering the findings of previous studies about the relationship between trunk kinematics, load lifted, muscle activity and spinal loading [7,10,18,21], it may be deduced that muscle activity may be altered to adjust for changes in the inertial force of the lifted box and lumbar angular position.

Critical lumbar angles

One of the main factors that increase the risk of injury in the lumbar zone of the spine is the increase in the imposed bending moment. As mentioned before, the lower trunk musculature generates the extension moment in order to compensate for the effects of imposed bending moment. Therefore, the critical lumbar angles and critical ranges of motion are those ones in which the lumbar extension moment reaches the peak values. As the results have shown, the peak extension moment depends on the peak linear acceleration of the lifted box, so critical lumbar angles and critical ranges of motion are those ones in which the inertial force of the lifted box reaches the peak values. The peak inertial force of the lifted box occurs at fast and sudden movement of the lifted box that implies fast trunk rotation and leads in jerky contractions of the lower trunk muscles which consequently increases the risk of injury. Although the lumbar angle affects the muscle activity, it doesn't seem, as the results have shown, to be as an independent influential factor in peak lumbar extension moment and risk of injury during lifting performance.

CONCLUSIONS

Findings of this study have provided more insight into the effects of external loading on the lumbar extension moment and lower trunk musculature activity during squat lifting. Moreover, the findings have contributed to determine the critical lumbar angles and critical ranges of motion in order to optimize the task performance and to prevent any risk of injury. As the results of this study have shown, the most important factor that affects the neuromuscular system of the lower trunk during lifting is inertial force of the lifted box, which in high levels would cause in jerky contractions of the muscles and consequently increases the risk of injury. In addition, the critical lumbar angles have appeared to be those ones in which the lifted box reaches the peak acceleration.

Practical application

Appropriate insight into the roles of the box weight and lift speed on performing a squat lifting may help subjects to control the movement during lifting performances.

Moreover, the natural patterns of lumbar extension moment and angular position of the joints enable clinicians to determine the critical lumbar angles which contribute to risk of injury of the lumbar spine. For example, regarding knowledge about the effects of box weight, lift speed and lifted box inertial force on the lumbar extension moment, subjects may become able to prevent the risk of injury with avoiding jerky movements during the lifting performance. In addition, the natural patterns of lower trunk musculature activity may be used by clinicians to diagnose abnormal lumbar muscular functions and also to determine lumbar muscular disorders in subjects during squat lifting.

Limitations

A limitation of this study has been that all participants were male and the BMI was limited to a specific range. Therefore, the results may have differed if the participants were female or if the BMI were limited to other ranges. Another study limitation was that the determined box masses and lift speeds of the study were in the limited ranges. Therefore, all findings of the study may be valid only for the determined box masses and lift speeds.

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REFERENCES

1. Macintosh JE, Bogduk N. The biomechanics of the lumbar multifidus. Clin Biomech. 1986;1:205–13, https://doi.org/10.1016/0268-0033(86)90147-6.
2. McGill SM, Patt N, Norman RW. Measurement of the trunk musculature of active males using CT scan radiography: Implications for force and moment generating capacity about the L4/L5 joint. J Biomech. 1988;21:329–41, https://doi.org/10.1016/0021-9290(88)90262-X.
3. Dumas GA, Poulin MJ, Roy B, Gagnon M, Jovanovic M. A three-dimensional digitization method to measure trunk muscle lines of action. Spine. 1988;13:532–41, https://doi.org/10.1097/00007632-198805000-00017.
4. Gatton M, Pearcy M, Pettet G. Modelling the line of action for the oblique abdominal muscles using an elliptical torso model. J Biomech. 2001;34(9):1203–7, https://doi.org/10.1016/S0021-9290(01)00079-3.
5. Crisco JJ, Panjabi JJ, Panjabi MM, Yamamoto I, Oxland TR. Euler stability of the human ligamentous lumbar spine. Part II: Experiment. Clin Biomech. 1992;7:27–32, https://doi.org/10.1016/0268-0033(92)90004-N.
6. McGill S. The biomechanics of low back injury: Implications on current practice in industry and the clinic. J Biomech. 1997;30(5):465–75, https://doi.org/10.1016/S0021-9290(96)00172-8.
7. Davis KG, Marras WS. Assessment of the relationship between box weight and trunk kinematics: Does a reduction in box weight necessarily correspond to a decrease in spinal loading? Human Factors. 2000;42(2):195–208, https://doi.org/10.1518/001872000779656499.
8. Hwang S, Kim Y, Kim Y. Lower extremity joint kinetics and lumbar curvature during squat and stoop lifting. BMC Musculoskelet Disord. 2009;2:10–5, https://doi.org/10.1186/1471-2474-10-15.
9. Dolan P, Adams MA. The relationship between EMG activity and extensor moment generation in the erector spinae muscles during bending and lifting activities. J Biomech. 1993;26(4–5):513–22, https://doi.org/10.1016/0021-9290(93)90013-5.
10. Marras WS, Mirka GA. A comprehensive evaluation of trunk response to asymmetric trunk motion. Spine. 1992;17:318–26, https://doi.org/10.1097/00007632-199203000-00013.
11. Seroussi RE, Pope MH. The relationship between trunk muscle electromyography and lifting moments in the sagittal and frontal planes. J Biomech. 1987;20(2):135–46, https://doi.org/10.1016/0268-0033(87)90016-7.
12. Fathallah FA, Marras WS, Parnianpour M. The role of complex, simultaneous trunk motions in the risk of occupa-

tion-related low back disorders. Spine. 1998;23(9):1035–42, https://doi.org/10.1097/00007632-199805010-00014.

13. Granata KP, Marras WS. The influence of trunk muscle co-activity on dynamic spinal loads. Spine. 1995;20(8):913–9, https://doi.org/10.1097/00007632-199504150-00006.
14. Kim JY, Marras WS. Quantitative trunk muscle electromyography during lifting at different speeds. Int J Ind Ergon. 1987;1:219–29, https://doi.org/10.1016/0169-8141(87)90016-3.
15. Marras WS, Granata KP. Changes in trunk dynamics and spine loading during repeated trunk exertions. Spine. 1997;22(21):2564–70, https://doi.org/10.1097/00007632-199711010-00019.
16. Marras WS, Sommerich CM. A three-dimensional motion model of loads on the lumbar spine. Part II: Model validation. Hum Factors. 1991;33(2):139–49.
17. Bush-Joseph C, Schipplein O, Andersson GBJ, Andriacchi TP. Influence of dynamic factors on the lumbar spine moment in lifting. Ergonomics. 1988;31:211–6, https://doi.org/10.1080/00140138808966662.
18. Kingma I, Baten CT, Dolan P, Toussaint HM, van Dieën JH, de Looze MP, et al. Lumbar loading during lifting: A comparative study of 3 measurement techniques. J Electromyogr Kinesiol. 2001;11:337–45, https://doi.org/10.1016/S1050-6411(01)00011-6.
19. Lavender SA, Andersson GBJ, Schipplein OD, Fuentes HJ. The effects of initial lifting height, load magnitude, and lifting speed on the peak dynamic L5/S1 moments. Int J Ind Ergon. 2003;31:51–9, https://doi.org/10.1016/S0169-8141(02)00174-9.
20. Mawston GA, Boocock MG. The effect of lumbar posture on spinal loading and the function of the erector spinae: Implications for exercise and vocational rehabilitation. J Physiother. 2012;40(3):135–40.
21. Lavender SA, Tsuang YH, Andersson GB. Trunk muscle activation and cocontraction while resisting applied moments in a twisted posture. Ergonomics. 1993;36(10):1145–57, https://doi.org/10.1080/00140139308967985.
22. Marras WS, Mirka GA. Electromyographic studies of the lumbar trunk musculature during the generation of low level trunk acceleration. J Orthop Res. 1993;11:811–7, https://doi.org/10.1002/jor.1100110606.
23. Marras WS, Mirka GA. Muscle activities during asymmetric trunk angular acceleration. J Orthop Res. 1990;8:824–32, https://doi.org/10.1002/jor.1100080607.
24. Walsh JC, Quinlan JF, Stapleton R, FitzPatrick DP, McCormack D. Three-dimensional motion analysis of the lumbar spine during “free squat” weight lift training. Am J Sports Med. 2007;35(6):927–32, https://doi.org/10.1177/0363546506298276.
25. Fathallah FA, Marras WS, Parnianpour M. The effect of complex dynamic lifting and lowering characteristics on trunk muscles recruitment. J Occup Rehab. 1997;7(3):121–38, https://doi.org/10.1007/BF02767359.
26. Marras WS, Lavender SA, Leurgans S, Fathallah F, Allread WG, Ferguson SA, et al. Biomechanical risk factors for occupationally related low back disorders. Ergonomics. 1995;38:377–410, https://doi.org/10.1080/00140139508925111.
27. Ng JK-F, Kippers V, Parnianpour M, Richardson CA. EMG activity normalization for trunk muscles in subjects with and without back pain. Med Sci Sports Exerc. 2002;34:1082–6, https://doi.org/10.1097/00005768-200207000-00005.
28. Ng JK-F, Parnianpour M, Richardson CA, Kippers V. Functional roles of abdominal and back muscles during isometric axial rotation of the trunk. J Orthop Res. 2001;19:463–71, https://doi.org/10.1016/S0736-0266(00)90027-5.
29. Shrout PE, Fleiss JL. Intraclass correlations: Uses in assessing rater reliability. Psychol Bull. 1979 Mar;86(2):420–8, https://doi.org/10.1037/0033-2909.86.2.420.
30. Tabakin D, Vaughan CL. A comparison of 3D gait models based on the Helen Hayes marker set. Proceedings of the sixth international symposium on the 3D analysis of human movement. Cape Town: 2000. p. 98–101.
31. De Looze MP, Kingma I, Bussmann JBJ, Toussaint HM. Validation of a dynamic linked segment model to calculate

joint moments in lifting. Clin Biomech. 1992;7:161–9, https://doi.org/10.1016/0268-0033(92)90031-X.

32. Domholdt E. Rehabilitation research principles and applications. 3rd ed. St. Louis, Mo: Elsevier Saunders; 2005.
33. Rossi DM, Morcelli MH, Marques NR, Hallal CZ, Gonçalves M, Laroche DP, et al. Antagonist coactivation of trunk stabilizer muscles during Pilates exercises. J Bodyw Mov Ther. 2014;18(1):34–41, https://doi.org/10.1016/j.jbmt.2013.04.006.
34. Bentley JR, Amonette WE, de Witt JK, Hagan RD. Effects of different lifting cadences on ground reaction forces during the squat exercise. J Strength Cond Res. 2010;24:1414–20, https://doi.org/10.1519/JSC.0b013e3181cb27e7.
35. McGill S, Sharrott MT. Relationship between intra-abdominal pressure and trunk EMG. Clin Biomech. 1990;5:59–67, https://doi.org/10.1016/0268-0033(90)90039-9.