EXERCISE SPECIFIC LOADING CONDITIONS AND MOVEMENTS OF SQUATS, LUNGES, GOODMORNINGS AND DEADLIFTS

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The purpose of this study was to compare the joint kinematics and loading conditions acting on the knee, hip and lumbar spine during several strength exercises; Squats, Split Squats, Deadlifts and Goodmornings. Kinematic and kinetic data were recorded using an optoelectronic system and force plates. Maximal range of motion and maximal external joint moment were calculated and examined. Using these findings, specific training programs can be prepared for athletes. Specifically, for prevention and rehabilitation of ACL injury, Goodmornings are preferentially suggested in order to shift the hamstrings-to-quadriceps ratio towards the hamstrings.

KEY WORDS: Loading conditions, kinematics, joint angles, range of motion, strength exercises.

INTRODUCTION: Multi-joint, closed-chain kinetic resistance exercises, including Squats, Lunges, Deadlifts (DLs) or Goodmornings (GMs) are commonly used in prevention programs for e.g. reducing the risk of ACL injury, or during rehabilitation in e.g. low back pain patients, as well as during training to increase an athlete's performance, where the loading conditions play an important role on both the passive and active musculoskeletal structures. Here, exercise kinematics plays a key role for governing the lifting mechanics, and therefore modulating the risk of injury and level of performance. In 1999 in Switzerland, the most frequent injuries during fitness training were the shoulder 24.4%, back 16.6%, thigh 11.0% and knee 8.8%. The reasons for injury could be predominantly attributed to overloading (45.6%) or incorrect execution of the exercises (21.1%) (Mueller, 1999). Despite these statistics, a complete biomechanical understanding of the loading conditions of many exercises during strength training remains lacking.

The Squat exercise has been analysed using two different types of execution; an "unrestricted squat" (s_{unr}), and a "restricted squat" (s_{res}), where the anterior part of the knees should not move beyond a vertical line over the toes in the sagittal plane. s_{res} is the more common variant, and is frequently used in fitness centres. However, the s_{unr} seems to be appropriate for most sportsmen (Fry, Smith, & Schilling, 2003; Lorenzetti et al., 2012). Split squats, or Lunges are commonly used in rehabilitation settings, particularly after cruciate ligament reconstruction (Escamilla et al., 2010), where step length and trunk position are known to affect loading conditions in the lower extremities (Escamilla et al., 2008; Schutz et al., 2014). The DL is a multi-joint resistance exercise that is performed in a variety of training settings (Swinton, Stewart, Agouris, Keogh, & Lloyd, 2011) and is one of the three disciplines in powerlifting. The GM exercise is an assistance movement utilized primarily by weight lifters to strengthen the extensors of the torso, the *glutei*, hamstrings and *erector spinae*.

To plan effective training routines with a low risk of injury, it is necessary to consider muscle groups, joint motion, muscle balance and coordination patterns (Zatsiorsky & Kraemer, 2006). In order to set a mechanobiological stimulus for a positive adaptation of a muscle, high individual stresses over the entire length range of the muscles are required. Therefore, exercises should be chosen, that produce large joint moments as well as large ranges of motion (RoMs) in the targeted joints and muscles, while still promoting low moments in the other joints. However, comprehensive knowledge of the loading conditions during such training exercises are lacking in the literature. Therefore, the aim of this study was to compare segmental kinematics and joint moments of the spine and the lower limbs between five strength exercises.

METHODS: Subjects, all experienced in weightlifting and movement science students, were analysed while performing s_{res}, s_{unr}, Lunges, DLs or GMs. For Squats, ten female and ten male subjects (24 ± 4 years, 66 ± 12 kg, 1.73 ± 0.08 m) with no history of back problems were examined (Lorenzetti et al., 2012). Four subjects were not included for further analysis due to missing data. During Lunges, five female and six male subjects (25 ± 2 years, 68 ± 9 kg, 1.76 ± 0.07 m) were analysed (Schutz et al., 2014). During DLs and GMs, four female and nine male subjects (25 ± 4 years, 74 ± 11 kg, 1.80 ± 0.07 m) were observed (Schellenberg, Lindorfer, List, Taylor, & Lorenzetti, 2013).

The four different studies (List, Gulay, Stoop, & Lorenzetti, 2013; Lorenzetti et al., 2012; Schellenberg et al., 2013; Schutz et al., 2014) were all approved by the Ethics committee of ETH Zurich, Switzerland. To analyse the motion of the body, an optoelectronic system (Vicon, Oxford Metrics Group, UK) with twelve cameras (MX40) was used. The ground reaction forces were measured using two 400×600 mm force plates (type 9281B Kistler, Winterthur Switzerland), one under each foot, recording at a frequency of 2 kHz. The IfB Marker Set (List et al., 2013), consisting of 55 markers on the legs, pelvis, shoulder and arms, 22 on the back (only for Squats, DLs and GMs) and 2 attached to the barbell, was used and attached by trained personnel. Subjects wore their normal training shoes throughout all tests.

The subjects received standardized instructions for each exercise. The different exercises were performed using additional extra load on the barbell corresponding to subjects' bodyweight (BW). An extra load of 25% BW on the bar was used for Squats, Lunges, DLs and GMs while Squats, Lunges and DLs were additionally performed with an extra load of 50% BW on the bar. The Lunges were performed with a step length of 70% of total leg length and a tibia angle to the ground of α=90° at the deepest position of the split squat (Schutz et al., 2014).

The joint centres of the knee and hip were functionally determined from the basic motion tasks (List et al., 2013), and the joint centre of L4/L5 was defined anatomically based on anthropometric data (Nissan & Gilad, 1986). The external joint moments in the sagittal plane were calculated using an inverse approach with a quasi-static solution (Zatsiorsky, 2002). The flexion / extension moments at the knees and hips were averaged over both limbs, except for the lunges, where the rear foot was differentiated from the rear one. The inverse approach included the position of the joints, the forces acting on each foot, and the gravitational force of the segments (Lorenzetti et al., 2012). All calculations were performed in Matlab (The MathWorks Inc., Natick, MA, USA).

A linear mixed model was used to evaluate all statistical parameters for each exercise. The model used the exercise type with the specific extra barbell load as a fixed effect and subjects as random effects. Bonferroni corrected pairwise comparisons were performed. Using the Bonferroni adjustment for the 11 dependent variables, the significance level was set at $p<0.0045$. The statistical evaluation of the data was performed using IBM SPSS software version 20 (SPSS AG, Zurich, Switzerland).

RESULTS AND DISCUSSION: Knee Kinematics: The observed RoMs of the knee in the sagittal plane were higher during DLs and s_{unr} (Table 1) compared to others (Table 2), while GMs show the smallest RoM (Table 1).

Knee kinetics: During DLs, s_{unr} as well as s_{res}, no changes between the two loading conditions (25% / 50% BW) on the barbell were found in the maximum moment about the knee in the sagittal plane (Table 2). However, Lorenzetti and co-workers (2012) showed significant weight dependence in s_{unr} as well as s_{res} in the knee due to the lower Bonferroni adjustment.

Table 1

Mean normalized maximal moments and its standard deviations [N*m/BW] and RoM [°] as well as the RoM and minimal curvature [1/m] in the sagittal plane about the knee, hip and L4/L5, lumbar and thoracic region, respectively for all exercises using 25% or 50% BW extra load.

	GM 25	DL 25	DL 50	S_{unr} 25	S_{unr} 50	S_{res} 25	S_{res} 50	Lun 25 front	Lun 25 rear
Max Knee Mom	-0.96 ± 0.21	1.11 ± 0.39	1.14 ± 0.45	1.28 ± 0.21	1.51 ± 0.20	0.96 ± 0.17	1.13 ± 0.17	1.14 ± 0.19	1.71 ± 0.21
Max Hip Mom	1.63 ± 0.14	1.40 ± 0.13	1.92 ± 0.19	0.98 ± 0.23	1.30 ± 0.31	1.12 ± 0.19	1.52 ± 0.25	1.71 ± 0.32	0.91 ± 0.23
Max L4/L5 Mom	2.75 ± 0.26	2.81 ± 0.27	3.77 ± 0.43	1.89 ± 0.37	2.51 ± 0.55	1.96 ± 0.35	2.70 ± 0.47		
Knee RoM	7.84 ± 5.50	103.40 ± 23.07	99.74 ± 21.69	102.37 ± 11.06	100.42 ± 8.37	80.41 ± 12.50	81.84 ± 13.45	70.36 ± 7.78	80.30 ± 11.70
Hip RoM	58.37 ± 10.01	90.41 ± 5.29	89.11 ± 5.90	82.36 ± 10.93	76.89 ± 10.99	81.30 ± 11.29	78.87 ± 12.34	46.51 ± 9.27	29.08 ± 7.64
PL RoM	16.75 ± 4.67	21.46 ± 4.35	19.18 ± 3.62	19.20 ± 5.58	17.02 ± 4.23	19.00 ± 5.30	17.31 ± 5.40		
LT RoM	9.82 ± 3.74	7.86 ± 2.85	8.66 ± 4.08	9.95 ± 3.40	8.97 ± 2.58	11.67 ± 4.39	10.99 ± 4.97		
curv L RoM	2.68 ± 1.30	2.75 ± 1.15	2.53 ± 0.91	1.99 ± 0.70	1.65 ± 0.59	2.19 ± 1.04	1.72 ± 0.73		
curv L min	0.36 ± 1.65	0.44 ± 1.30	0.35 ± 1.04	1.42 ± 1.76	1.59 ± 1.82	1.37 ± 2.36	1.35 ± 2.20		
curv T RoM	0.89 ± 0.55	0.58 ± 0.27	0.57 ± 0.32	0.97 ± 0.49	0.94 ± 0.48	1.22 ± 0.69	1.08 ± 0.68		
curv T min	1.28 ± 0.64	1.70 ± 0.77	1.75 ± 0.81	1.38 ± 1.02	1.47 ± 1.07	1.05 ± 1.23	1.29 ± 1.27		

Table 2

Significances ($p<0.0045$) between the different exercises.

DL 25	DL 50	S_{unr} 25	S_{unr} 50	S_{res} 25	S_{res} 50	Lun 25 front	Lun 25 rear	
km, hm kr, hr, plr	km, hm, lm kr, hr	km, hm, lm kr, hr	km kr, hr	km, hm, lm kr, hr	km kr, hr	km kr	km, hm kr, hr	GM 25
	hm, lm	hm, lm	km	lm kr	kr	kr, hr	km, hm hr	DL 25
		hm, lm	hm, lm	hm, lm	hm, lm	kr, hr	km, hm hr	DL 50
			hm, lm	km kr, tmc	hm, lm kr	hm kr, hr	km hr	S_{unr} 25
				km, lm kr	km, hm kr	hm kr, hr	hm hr	S_{unr} 50
					hm, lm	hm hr	km hr	S_{res} 25
						hr	km, hm hr	S_{res} 50
							km, hm hr	Lun 25 front

km	Knee Moment
hm	Hip Moment
lm	L4/L5 Moment
kr	RoM Knee
hr	RoM Hip
plr	RoM Pelvis-Lumbar
ltr	RoM Lumbar-Thoracic
lrc	RoM Lumbar Curvature
lmc	Min Lumbar Curvature
trc	RoM Thoracic Curvature
tmc	Min Thoracic Curvature

Hip kinematics: DLs and Squats (s_{unr} and s_{res}) showed the highest RoMs; while during lunges (front and rear foot) smaller RoMs were observed (Table 1).
Hip kinetics: All moments at the hip of all exercises in the sagittal plane were external flexion moments (Table 1). DLs using 50% BW and the front leg of the lunges led to the highest flexion moment followed by GMs using 25% BW extra load (Table 1).
Back kinematics: No kinematic differences in the back could be observed except the pelvic relative to lumbar segmental RoM of DLs using 25% BW extra load to GMs using the same amount on the barbell (Table 2). However, List and co-workers (2013) showed a difference in the segmental rotations RoMs from s_{unr} to s_{res} due to a smaller significance level ($p<0.05$).
Back kinetics: DLs produced the highest moment in L4/L5 and were weight dependent (Table 2) followed by GMs with 25% BW and squats (s_{unr} and s_{res}) using 50% BW extra load (Table 1).

CONCLUSION: Knee training relevant outcomes: To specifically train the knee with the application of high RoMs as well as high joint moments, s_{unr} should be used, while DLs should be performed if the RoM is important. On the other hand, Lunges (rear foot) should be chosen if a high knee moment is required (Table 1). Performing GMs led to an external extension moment in the knee with only a small RoM, and should therefore be chosen to strengthen the Hamstrings (Table 1).

Hip training relevant outcomes: DLs with 50% BW extra load on the barbell should be chosen to train the hip in a large RoM, and with a high external flexion moment. If a large RoM is preferable, DLs with 25% BW extra load or squats (s_{unr} and s_{res}) with 50% BW extra load should also be taken into account. However, GMs or lunges, especially the front leg, should be chosen if the RoM is secondary and a higher moment in the hip is more important (Table 1). For prevention of ACL injuries, GMs are recommended for training the hamstrings to quadriceps ratio towards hamstrings.

Back Training relevant outcomes: For the exercises GMs, DLs with 25% BW, s_{unr} with 50% BW and s_{res} with 50% BW extra load, no kinetic and kinematic differences in the back (except the difference of the pelvic relative to lumbar segmental RoM of DLs to GMs) were observed. Therefore, from a biomechanical point of view, the mentioned exercises above produce similar loading conditions and motions for the trunk. To enhance the strength of m. *erector spinae*, the use of DLs and GMs are recommended, since the highest moment was observed in L4/L5 compared with other exercises using the same extra weight on the bar (Table 1). Great care should be taken to ensure core stability of the trunk during lifting due to high loading of the spine, especially when training with higher extra loads.

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