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Scapular kinematics during unloaded and maximal loaded isokinetic concentric and eccentric shoulder flexion and extension movements

Monique Wochatz[a,*], Sophie Rabe[b], Tilman Engel[a], Steffen Mueller[c], Frank Mayer[a]

[a] University of Potsdam, University Outpatient Clinic, Sports Medicine and Sports Orthopaedics, Am Neuen Palais 10 – Haus 12, D-14469 Potsdam, Germany
[b] University of Potsdam, Center of Rehabilitation Research, Am Neuen Palais 10 – Haus 12, D-14469 Potsdam, Germany
[c] Trier University of Applied Science, Department of Computer Science/Therapy Science, Schneidershof, Gebäude L, Germany

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ABSTRACT

Characterization of scapular kinematics under demanding load conditions might aid to distinguish between physiological and clinically relevant alterations. Previous investigations focused only on submaximal external load situations. How scapular movement changes with maximal load remains unclear. Therefore, the present study aimed to evaluate 3D scapular kinematics during unloaded and maximal loaded shoulder flexion and extension. Twelve asymptomatic individuals performed shoulder flexion and extension movements under unloaded and maximal concentric and eccentric loaded isokinetic conditions. 3D scapular kinematics assessed with a motion capture system was analyzed for 20° intervals of humeral positions from 20° to 120° flexion. Repeated measures ANOVAs were used to evaluate kinematic differences between load conditions for scapular position angles, scapulohumeral rhythm and scapular motion extent. Increased scapular upward rotation was seen during shoulder flexion and extension as well as decreased posterior tilt and external rotation during eccentric and concentric arm descents of maximal loaded compared to unloaded conditions. Load effects were further seen for the scapulohumeral rhythm with greater scapular involvement at lower humeral positions and increased scapular motion extent under maximal loaded shoulder movements. With maximal load applied to the arm physiological scapular movement pattern are induced that may imply both impingement sparing and causing mechanisms.

1. Introduction

Many studies established typical scapular motion presenting evidence for continuous scapular upward rotation, posterior tilting and external rotation while the arm elevates overhead (Ludewig et al., 2009, 1996; McClure et al., 2001). Alterations from this movement pattern are generally assumed to be associated with shoulder pain and pathologies like impingement syndrome, rotator cuff disease and glenohumeral instability (Ludewig and Reynolds, 2009; Struyf et al., 2011). However, study results vary regarding scapular kinematic alterations in comparison to asymptomatic healthy controls and thus lack to present constant pattern (Ludewig and Reynolds, 2009; Ratcliffe et al., 2014). Which role scapular position and movement alterations have in relation to shoulder pathologies and whether observed deviations may represent physiological variability is under debate. To be able to differentiate between physiological variability and clinically relevant alterations it is necessary to characterize scapular kinematics for shoulder joint representative conditions in asymptomatic individuals first. Loading over short or long term seem to have an influence on the shoulder complex. Studies could show that continues loading during a training session and fatigue of the shoulder musculature can initiate scapular alterations in asymptomatic athletic and non-athletic individuals (Chopp et al., 2011; Ebaugh et al., 2006; Madsen et al., 2011; Rich et al., 2016). Further, scapular position and movement alterations are more frequently seen in overhead athletes and overhead workers while showing an increased prevalence of shoulder pain in comparison to populations that not repetitively load their shoulder (Bernard, 1997; Burn et al., 2016; van Rijn et al., 2010). Thus, evaluation of scapular kinematics in situations with higher loads applied to the upper extremity as demanded in overhead sports and work would contribute to a more comprehensible understanding of physiological scapular movement pattern and might help to recognize clinically relevant alterations. Previous studies that

* Corresponding author.
E-mail addresses: wochatz@uni-potsdam.de (M. Wochatz), srabe@uni-potsdam.de (S. Rabe), tiengel@uni-potsdam.de (T. Engel), Stef.Mueller@inf.hochschule-trier.de (S. Mueller), fmayer@uni-potsdam.de (F. Mayer).

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investigated the effect of additional external loads on scapular position and movement showed inconsistent results. Some studies (de Castro et al., 2014; de Groot et al., 1999; Kai et al., 2016; Michiels and Grevenstein, 1995) reported no differences in scapular orientation or movement between unloaded and loaded humerus positions whereas others (Camci et al., 2013; Forte et al., 2009; Kon et al., 2008; McQuade and Smidt, 1998; Pascoal et al., 2000) identified scapular motion adaptations in response to additional load applied to the arm. The direction and magnitude of scapular movement alterations varied across studies showing reduced scapular upward rotation and posterior tilt as well as increased upward rotation and posterior tilt with additional load. Differences in study outcomes may be attributed to methodological differences in scapular kinematic determination methods, the assessed motion and movement plane and the loads applied. It further has to be considered that in general, the assessment of scapular kinematics is challenging, as movements occur beneath skin and muscles. Intracortical bone pins overcome those methodological issues and are therefore generally accepted as the most accurate and valid method to capture scapular motion (Ludewig et al., 2009; McClure et al., 2001). Even though knowing that non-invasive methods with sensors or markers mounted to anatomical landmarks on the skin over- or underestimate actual scapular rotations to some extent (Karduna et al., 2001), those electromagnetic and optoelectronic techniques are most frequently used in clinical and research context. Depending on the marker position and the movement being assessed, studies could show that dynamic scapular kinematics can be tracked with moderate to good reliability (Bourne et al., 2011; Brochard et al., 2011; Lempereur et al., 2012; van Andel et al., 2009). Studies that investigated the effect of additional loads on scapular motion focused only on submaximal loads and the scapular motion during arm elevation mostly neglecting load situations during arm lowering. It is unknown whether and if so, how scapular kinematics alter with maximum effort arm movements that represent a tremendous demand on both coordination and stability on the shoulder complex.

Therefore, it is the aim of the present study to evaluate 3D scapular kinematics during unloaded and maximal loaded concentric and eccentric shoulder flexion and extension movements in asymptomatic adults. It is of particular interest to investigate adaptations on (a) scapular position angles, (b) scapulohumeral rhythm and (c) the extent of scapular motion in response to maximum effort arm movements.

2. Methods

2.1. Subjects

Twelve healthy asymptomatic adults (males: 7, females: 5; 29 ± 4 years; 177 ± 13 cm; 76 ± 16 kg) were recruited from a sample of convenience out of a university setting. Participants were physically active (4 ± 3 h per week) in a variety of sports (strength training, running, calisthenics, cycling, horse riding, soccer, basketball and yoga) excluding focused overhead throwing activities. Recent musculoskeletal complains of the upper limb, impaired arm movement during daily activities or sports, upper limb surgery within the last 6 month or acute or chronic infections prevented individuals from participation. All involved individuals were informed about the aim and the content of the study and received and signed written informed consent about their voluntary participation. The institutional research committee gave approval for the conduction of the present study.

2.2. Instrumentation

Cross-sectional assessment of 3D scapular kinematics was conducted during an isokinetic shoulder flexion and extension movement of the dominant arm in scapular plane (45° out of the frontal plane). Isokinetic movements were performed in a standing position with the shoulder aligned to the rotational axis of the dynamometer (Con-Trex, WS, Physiomed AG Germany) the elbow extended and the pronated hand holding the handle of the adapter. The range of motion was set to 20–180° shoulder flexion. Motion analysis was performed with a 3D motion capture system consisting of 7 cameras (Vicon, Oxford, UK, MX T10S; 500 Hz) and a reflective marker setup (12 markers) based on the ISB recommendations of joint coordinate systems in reporting joint motion (Beitzel et al., 2014; Wu et al., 2005). Markers were attached to the skin of bony landmarks to assess motion of the thorax, upper arm and scapula (see Table 1 for detailed description). In addition to the recommended landmarks for the assessment of the humerus a custom-made arm cuff with three markers aligned to an equilateral triangle was attached to the upper arm. A schematic overview of the laboratory setting, and the applied marker setup are given in Fig. 1A and B, respectively.

2.3. Procedure and measurement protocol

Prior to inclusion, a physical examination by a physician was performed to confirm pain free and unrestricted shoulder movements. After preparing participants with the marker setup they were aligned to the isokinetic device. The isokinetic protocol comprised a familiarization of continues submaximal shoulder flexion and extension movements followed by unloaded and maximal loaded movements. The unloaded condition was conducted as "continuous passive motion" (CPM), where the dynamometer guided the participants movement in respect to the predefined ROM and the motion velocity. For this condition participants were asked to actively move their arm with the device without applying additional resistance on the adapter. The dynamometer thereby moved through the ROM without the initiation or force application of the participant. Maximal load conditions were conducted during concentric (CON) and eccentric (ECC) modes. For these conditions, participants were asked to move their arm with maximum effort through the ROM, which meant for the CON mode trying to move the arm with maximum force from extension to flexion and vice versa and for the ECC mode trying to withstand the movement of the dynamometer ("attempt to stop device"). All movements were performed at a velocity of 60°/s and in continuous alternating manner of 5 repetitions each, separated by a one-minute break. The described measurement setup and protocol was already used in previous studies of the working group (Wochatz et al., 2017).

Table 1
Marker setup for the assessment of thorax, scapula and upper arm segment.

Segment	Marker	Anatomical landmark
Thorax	C7	Processus Spinosus of the 7th cervical vertebra
	Th8	Processus Spinosus of the 8th thoracic vertebra
	Sternum Cranial	Deepest point of the Incisura Jugularis (suprasternal notch)
	Sternum Caudal	Processus Xiphoideus, most caudal point of the sternum
Scapula	Angulus Inferior	Most caudal point of the scapula
	Angulus Acromialis	Most laterodorsal point of the scapula
	Scapula Spine	Trigonum Spinae Scapulae, midpoint of the triangular surface on the medial border of the scapula in line with the scapular spine
	Margo Medialis	Midpoint of trigonum spinae scapulae and angulus inferior at the medial border of the scapula
Upper Arm	AC Joint	Most dorsal point on the acromioclavicular joint (shared with scapula)
	Arm Cuff – 3 markers set to an equilateral triangle	Alignment of cuff with superior marker on insertion of musculus deltoideus at Tuberositas deltoidea

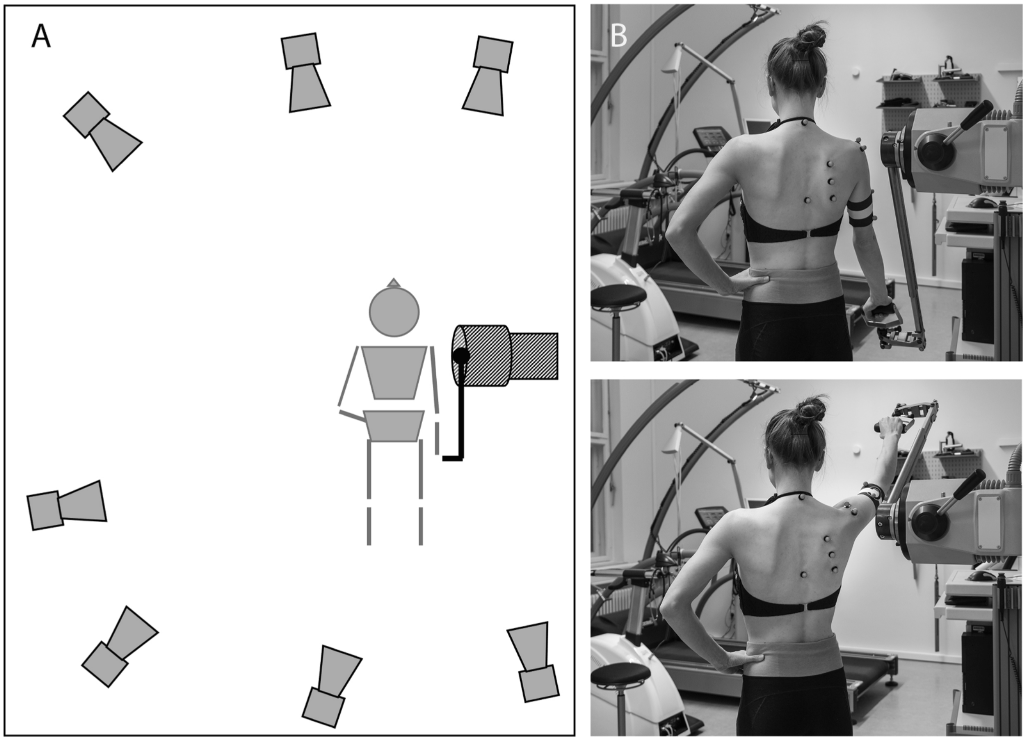

Fig. 1. Schematic overview of laboratory setting (A) with cameras, isokinetic dynamometer and participant position. Back view of markers (B) applied to anatomical landmarks for trunk, scapula and upper arm.

2.4. Data analysis and statistics

Kinematic data was recorded and analyzed with the Vicon Nexus Software (Version 2.0). Trajectories of the kinematic raw data were processed with a Woltring quintic spline interpolation. Based on the marker setup a thorax, upper arm and scapula segment were created. Segment rotations were calculated for the scapula and the humerus in relation to the thorax whereas Euler angles were calculated according to the rotation sequence X-Z-Y. The segment rotation of the scapula around the x-axes represents upward/downward rotation (positive values = upward rotation), around the y-axes anterior/posterior tilt (positive values = anterior tilt) and around the z-axes external/internal rotation (positive values = external rotation). 3D scapular position angles were given for each 10° increment of arm raising and lowering between the humerus position of 20° and 120° flexion. For each testing condition rotation angles were averaged over the five repetitions. In order to assess differences between scapular movement under unloaded and maximal loaded shoulder flexion and extension movements single comparisons of 3D scapular rotation angles were made for every 20° increments of humerus movement between 20° and 120°. To further characterize the scapular movement pattern the extent of angular scapular motion from 20° to 120° were summed up to a value representing the entire movement irrespective of the motion plane (t-RoM_{sum} [°]) and for each scapular movement plane separately (RoM_{sum} [°]). Scapulohumeral rhythm (SHR) was as well calculated for each movement plane, representing the relation between the extent of scapular and humerus motion. For every 20° of humerus motion (intervals: 20–40°, 40–60° etc.) the corresponding interval of scapular motion was used to create a ratio (humerus motion/scapular motion) that decreases with greater and increases with lesser contribution of scapular motion.

Variability of the 3D scapular angle assessment was evaluated within and between sessions for the three different loading conditions. Therefore, 10 of the 12 participants repeated the protocol on a second measurement day (8 ± 2 days after the first measurement (M1)). Intra-class correlation coefficient (ICC, 3.1) and minimal detectable change (MDC) were calculated. Additionally, a Bland and Altman analysis with bias and limits of agreement (LoA, bias + 1.96*SD; bias-1.96*SD) was conducted for inter-session reliability. For the comparison of scapular kinematic movement pattern during different loading conditions data were initially analyzed descriptively (mean (SD)). A two-way repeated measures ANOVA as well as adjusted paired t-tests ($\alpha = 0.016$) were applied for the evaluation of differences between the tested conditions. The inter-action effect of the test condition (CPM, CON, ECC) and the humerus position was used to clarify whether the scapular position angle and the SHR depend on the applied load and the specific position of the humerus during a movement of shoulder flexion and extension. The analysis was done for each scapular motion plane separately. Whether the extent of scapula motion depends on the loading condition (t-RoM_{sum}) and whether one motion plane is more affected than the other (RoM_{sum} of each scapular plane) was evaluated via one-way and two-way repeated measures ANOVA (inter-action effect: condition*-plane), respectively.

3. Results

3.1. Reliability of scapular motion assessment

Reliability of scapular position angles was comparable between shoulder flexion and extension with ICCs ranging from 0.60 to 0.98 and MDCs of up to 4.5° for assessments within a session and ICCs ranging from 0.30 to 0.98, MDCs of up to 7.7°, systematic error of up to −4.1° (bias) and random errors between −16° and 7.5° (LoA) for assessments between sessions irrespective of scapular motion plane and loading condition. Reliability decreased with increasing humerus position indicated by lower ICCs, greater MDCs and wider LoAs. Variability within and between sessions was further influenced by the loading condition with lowest deviations for CPM and highest for ECC as well as by the scapular motion plane. In relation to the total ROM of the scapula during shoulder flexion and extension scapular movement in upward/downward rotation showed lowest variability followed by scapular movement in anterior/posterior direction and greatest variability for movements in external/internal rotation.

3.2. Influence of loading condition on scapular position angles

Scapular movement courses of each single plane and condition for both shoulder flexion and extension are depicted in Fig. 2. Scapular position angles for each assessed humerus position in all three movement planes and conditions for shoulder flexion and extension are given in Tables 2A and 2B. Movement courses of each individual are shown in the supplementary material (*Fig. S-1, Fig. S-2*).

During shoulder flexion when the arm gets raised the scapula continuously rotated upwards, tilted posteriorly and rotated externally, regardless of the loading condition. During shoulder extension when the arm gets lowered the scapula accordingly rotated downwards, tilted anteriorly and rotated internally. Besides that, the course of the scapula movement followed similar patterns ANOVAs revealed differences in scapular position angles at distinct humerus positions between the loading conditions. Significant deviations were seen for scapular position angles in upward/downward direction for both shoulder flexion and extension ($F(10, 110) = 17.39$, $P < 0.001$; $F(10, 110) = 9.25$, $P = 0.001$). During shoulder flexion significant greater scapular upward rotation was seen for ECC in comparison to CPM at 20° humerus flexion, for CON and ECC in comparison to CPM at 40°, 60°, 80° and 100° humerus flexion and for CON in comparison to ECC and CPM at 120° humerus flexion. During shoulder extension deviations between unloaded and maximal loaded conditions were seen for all humerus positions with greater scapular upward rotation for CON in comparison to CPM over the entire course of the movement (120–20° humerus flexion) and for ECC in comparison to CPM at 120°, 100°, 80° and 60° humerus flexion. Scapular position angles in anterior/posterior direction and external/internal direction did not differ significantly between the loading conditions during shoulder flexion ($F(10, 110) = 2.72$, $P = 0.068$; $F(10, 110) = 3.63$, $P = 0.054$). During shoulder extension significant differences occurred in anterior/posterior direction ($F(10, 110) = 7.74$, $P < 0.001$) showing scapular position angles with less posterior tilt for ECC in comparison to CPM from 100° to 20° humerus flexion and in comparison to CON at 40° and 20°. Significant differences between the loading conditions in external/internal direction ($F(10, 110) = 16.79$, $P < 0.001$) were seen with greater scapular external rotation for CON in comparison to ECC at 120° and fewer external rotation in comparison to CPM at 60°, 40° and 20° and in comparison to ECC as well at 40° and 20° humerus flexion.

3.3. Influence of loading condition on the extent of scapular motion (RoM_{sum})

One-way repeated measures ANOVA indicated significant differences for t-RoM_{sum} of the test conditions during shoulder flexion ($F(2, 22) = 42.63$, $P < 0.001$) with greatest t-RoM_{sum} seen for CON and during shoulder extension ($F(2, 22) = 18.67$, $p < 0.001$) with greater t-RoM_{sum} for CON and ECC in comparison to CPM. Differences between the

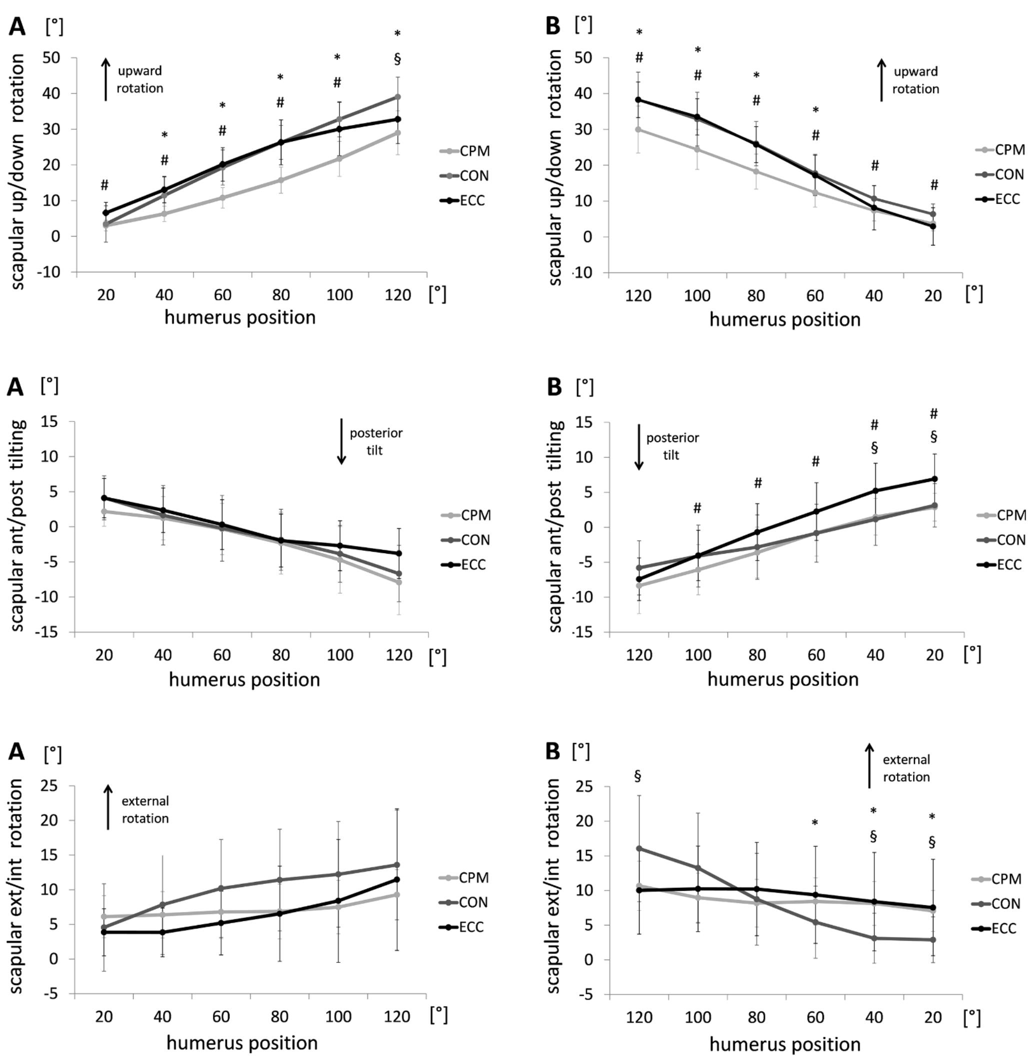

Fig. 2. Scapular motion (mean (SD)) in upward/downward rotation (up/down rotation), anterior/posterior tilt (ant/post tilt) and external/internal rotation (ext/int rotation) of isokinetic shoulder flexion (A) and extension (B) movements. (CPM = continuous passive motion (guided motion without resistance); CON = concentric shoulder movement with maximum effort; ECC = eccentric shoulder movement with maximum effort; upward/downward rotation: positive values indicate upward rotation; anterior/posterior tilt: positive values indicate anterior tilting; external/internal rotation: positive values indicate external rotation; "*" = indicates significant differences between CPM and CON; "#" = indicates significant differences between CPM and ECC; "§" = indicates significant differences between CON and ECC; α = 0.016).

Table 2A
3D scapular motion (mean (SD)) of isokinetic shoulder flexion in the scapular plane at according humerus positions (20–120°).

[°]	Upward/downward rotation						Anterior/posterior tilting						External/internal rotation					
	CPM		CON		ECC		CPM		CON		ECC		CPM		CON		ECC	
20	3.0	(1.5)	3.4	(5.1)	6.6	(2.9)	2.2	(2.1)	4.1	(3.1)	4.1	(2.8)	6.1	(3.0)	4.6	(6.3)	3.9	(3.4)
40	6.3	(2.2)	11.4	(5.4)	13.0	(3.6)	1.2	(3.1)	1.6	(4.2)	2.4	(3.2)	6.4	(3.4)	7.8	(7.2)	3.8	(3.5)
60	10.8	(2.9)	19.2	(4.9)	20.1	(4.7)	−0.3	(3.6)	−0.2	(4.7)	0.3	(3.5)	6.8	(3.8)	10.2	(7.1)	5.2	(4.6)
80	15.7	(3.7)	26.3	(4.7)	26.3	(6.3)	−2.3	(4.4)	−1.9	(4.4)	−2.0	(3.8)	6.9	(4.0)	11.4	(7.3)	6.5	(6.9)
100	21.7	(4.9)	32.8	(4.9)	30.0	(7.5)	−4.7	(4.7)	−3.9	(4.0)	−2.7	(3.6)	7.5	(3.9)	12.2	(7.6)	8.4	(8.9)
120	29.0	(6.1)	39.0	(5.6)	32.8	(6.8)	−7.9	(4.6)	−6.7	(4.0)	−3.8	(3.6)	9.3	(3.6)	13.6	(7.9)	11.5	(10.2)

(CPM = continuous passive motion (guided motion without resistance); CON = concentric shoulder movement with maximum effort; ECC = eccentric shoulder movement with maximum effort; upward/downward rotation: positive values indicate upward rotation; anterior/posterior tilting: positive values indicate anterior tilting; external/internal rotation: positive values indicate external rotation).

Table 2B
3D scapular motion (mean (SD)) of isokinetic shoulder extension in the scapular plane at according humerus positions (20–120°).

[°]	Upward/downward rotation						Anterior/posterior tilting						External/internal rotation					
	CPM		CON		ECC		CPM		CON		ECC		CPM		CON		ECC	
20	3.7	(2.0)	6.4	(2.9)	2.9	(5.2)	2.9	(2.0)	3.1	(3.1)	6.9	(3.6)	7.1	(3.0)	2.9	(3.3)	7.5	(6.9)
40	7.3	(2.9)	10.7	(3.6)	8.1	(6.2)	1.5	(2.6)	1.1	(3.7)	5.2	(3.9)	8.1	(3.2)	3.1	(3.6)	8.4	(7.1)
60	12.4	(4.1)	17.8	(5.3)	17.2	(5.6)	−0.8	(3.3)	−0.9	(4.1)	2.2	(4.1)	8.4	(3.4)	5.4	(5.2)	9.4	(7.0)
80	18.3	(4.9)	26.0	(6.2)	25.8	(5.0)	−3.6	(3.6)	−2.8	(4.6)	−0.7	(4.1)	8.2	(3.4)	8.7	(6.6)	10.2	(6.7)
100	24.4	(5.6)	32.9	(7.5)	33.5	(5.1)	−6.1	(3.6)	−4.1	(4.4)	−4.0	(3.6)	9.0	(3.6)	13.2	(7.9)	10.2	(6.2)
120	30.0	(6.6)	38.3	(7.7)	38.3	(5.0)	−8.4	(4.0)	−5.8	(3.9)	−7.4	(3.1)	10.7	(3.5)	16.0	(7.7)	10.0	(6.3)

(CPM = continuous passive motion (guided motion without resistance); CON = concentric shoulder movement with maximum effort; ECC = eccentric shoulder movement with maximum effort; upward/downward rotation: positive values indicate upward rotation; anterior/posterior tilting: positive values indicate anterior tilting; external/internal rotation: positive values indicate external rotation).

conditions were further dependent on the movement plane (Fig. 3; interaction effect; shoulder flexion: $F(4, 44) = 8.44$, $P < 0.001$; shoulder extension: $F(4, 44) = 10.16$, $P < 0.001$). During shoulder flexion significant greater RoM_{sum} was seen in upward/downward direction for CON in comparison to the other conditions as well as greater RoM_{sum} for CON and ECC in relation to CPM in external/internal direction. During shoulder extension significant greater RoM_{sum} was seen in upward/downward direction for CON and ECC in comparison to CPM, in anterior/posterior direction for ECC in comparison to CON and CPM and in external/internal direction for CON in comparison to ECC and CPM.

3.4. Influence of loading condition on scapulohumeral rhythm (SHR)

Significant SHR differences between the conditions were seen for scapular upward rotation during shoulder flexion ($F(8, 88) = 4.05$, $P = 0.032$). SHR continuously decreased from 3.7 to 1.5 with increasing humerus position during CPM, whereas SHR during CON remained constant, ranging from 1.3 to 1.9 over the course of the movement. SHR during ECC ranged between 1.5 and 1.9 for movement phases of 20–40°, 40–60° and 60–80° and increased up to a SHR of 5.3 in the last two movement phases. Statistically significant differences occurred in the first three phases with CPM being higher than CON and ECC and ECC being higher than CON between 20° and 40° humerus flexion, with CPM being higher than CON and ECC between 40° and 60° and with CPM being higher than CON between 60 and 80°. SHR differences in other motion planes during shoulder flexion and extension were not statistically significant. SHR for each movement interval and each movement plane for both shoulder flexion and extension are detailed in the Supplements (*Table S-1A, Table S-1B*).

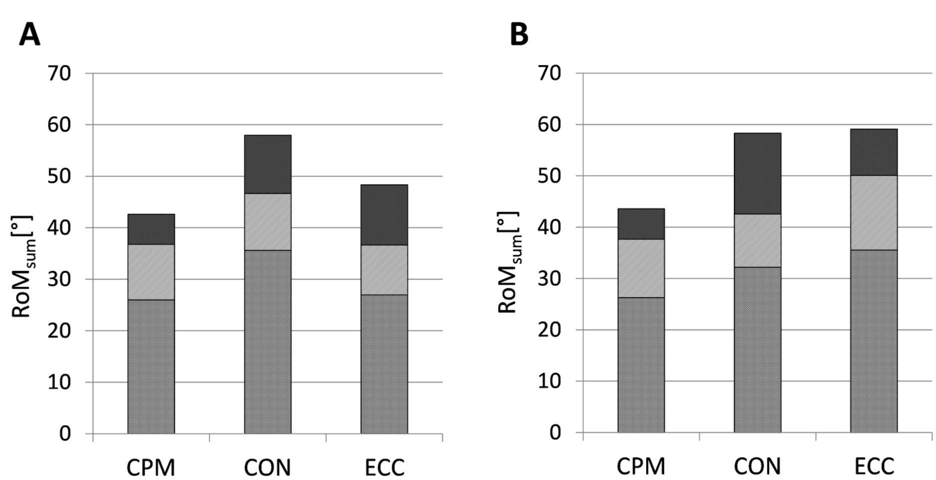

Fig. 3. Scapular motion extent (RoM_{sum}; mean) of isokinetic shoulder flexion (A) and extension (B) movements for scapular upward/downward rotation (dark grey bar section), anterior/posterior tilt (light grey bar section) and external/internal rotation (black bar section). (CPM = continuous passive motion (guided motion without resistance); CON = concentric shoulder movement with maximum effort; ECC = eccentric shoulder movement with maximum effort).

4. Discussion

The present study could show that the loading situation has an influence on scapular movement pattern. Scapular position angles changed in response to maximum effort and thereby showing greater upward rotation during shoulder flexion and extension, less posterior tilt and more as well as less external rotation over the course of shoulder extension. Identified differences between maximal loaded and unloaded conditions were specific to work type and humeral position. In accordance with the differences in scapular position angles the scapular motion extent increased from unloaded to maximal loaded shoulder flexion and extension mainly evoked by greater upward/downward rotation as well as greater tilting for eccentric and greater external/internal rotation for concentric loading during shoulder extension. The loading situation further had an influence on the relationship of humerus and scapular motion by altering the contribution of the scapula during movement phases up to shoulder level with more involvement of the scapula seen during maximal loaded conditions of shoulder flexion. The present study showed with mean differences of up to 9°(4°) for scapular upward rotation, 4°(4°) for scapular tilt and 6°(5°) for external rotation that deviations of physiological scapular movement pattern under various load situations in asymptomatic individuals resemble magnitudes of differences evaluated between individuals with and without shoulder pathologies (Borstad and Ludewig, 2002; Ludewig and Cook, 2000; Mcclure and Michener, 2006). Detected changes between the load conditions might be seen relevant as magnitudes of alterations exceeded measurement variability of MDCs ranging from 1° to 5° between repetitions on the same day and MDCs ranging from 1° to 8° between different measurement days. Even though maximum effort conditions added variability to the assessment of scapular kinematics, reliability was overall comparable to other skin-mounted marker techniques capturing scapular motion under unloaded static or dynamic shoulder movement tasks (Bourne et al., 2011; Brochard et al., 2011; Lempereur et al., 2012; van Andel et al., 2009). In those studies, good to excellent correlations of arm elevation tasks could be identified with MDCs up to 3° within a session and poor to good correlations with errors ranging from 3° to 8° (RMS error and SEM) depending on the scapular rotation and the humeral position. The presented results follow the general established pattern of continuous scapular upward rotation, posterior tilt and external rotation during arm rising and the reverse during arm lowering. Scapular rotations especially during the CPM condition are comparable to previous investigations of dynamic unloaded arm motion in the scapular plane where motion extents lie between 30° to 40° for scapular upward rotation, between 4° and 19° for posterior tilt and between 2° and 10° for external rotation. However, scapular kinematic assessments via bone pins demonstrate scapular motion of greater magnitude (approx. upward rotation: 35–38°; posterior tilt: 16°; external/internal rotation: 3–8°) (Ludewig et al., 2009; McClure et al., 2001). An underestimation of actual scapular position angles should be considered for the clinical interpretation and might be acknowledged as a methodological limitation of the present investigation (Karduna et al., 2001).

The present study investigated the effect of external load with maximum effort whereas previous studies mainly focused on submaximal load situations. Therefore, it is not surprising that the presented effect on scapular motion is only partially reflected in a few previous studies. Investigations by Forte et al. and Pascoal et al. showed as well increased scapular upward rotation during loaded conditions by greater position angles (Forte et al., 2009; Pascoal et al., 2000). Whereas Forte et al. revealed greater upward rotation at lower humeral positions (60°, 90°) Pascoal et al. reported an effect of load on scapular upward rotation dependent on the humeral position but without further specification. In contrast to the present study Forte et al. (at 60° humerus position) and Pascoal et al. (interaction between load and humerus position, but not specified) detected differences in scapular posterior tilt and external rotation of arm elevation. The magnitude of identified differences was unfortunately not reported. It needs to be considered that in contrast to the present study both investigations assessed scapular kinematics during static arm elevation with loads of up to 4kgs and showed alterations for movements in sagittal and frontal plane. A study by McQuade and Smidt, with a similar methodological approach as the present study, evaluated scapular kinematics during arm elevation in the scapular plane under an unloaded, passively moved and heavy loaded condition (McQuade and Smidt, 1998). With a cable and pulley mechanism attached to an isokinetic dynamometer maximum resistive arm elevation was applied. Differences between the conditions occurred over the entire course of movement (approx. 130°) however, heavily loaded in comparison to unloaded arm elevation resulted only in greater scapular involvement in the first movement phase (0–20% of maximum elevation). McQuade and Smidt presented overall higher SHR ratios in comparison to the present study, indicating less absolute scapular motion (McQuade and Smidt, 1998). Those differences might be related to different movement phase definitions (20° intervals of up to 120° elevation vs. 20% intervals of 100% with maximum arm elevation of approx. 130°). However, both studies are in agreement showing higher scapular involvement in the beginning of arm elevation and thereby indicating that loading with maximum effort rather effects the relationship of humerus and scapular motion at lower humeral positions. Other studies proved as well scapular movement alterations due to external loading of the arm, however verifying decreased upward rotation and external rotation (Camci et al., 2013; Kon et al., 2008). Kon et al. assessed scapular upward rotation via CT scans and revealed increased SHR between 5° and 65° humeral elevation with significant less scapular upward rotation for humeral positions of 35° and 45° for the load condition (Kon et al., 2008). Camci et al. investigated the effect of external load applied via a resistance band during arm rising and lowering showing as well reduced scapular upward rotation of up to 4° at humeral positions of 30°, 60° and 90° (Camci et al., 2013). Effects were further apparent for scapular external rotation with small average decreases of 1.4° under loaded conditions. Effects were seen for raising and lowering, but more pronounced during the lowering movement. Based on reduced scapular upward rotation at lower humeral angles Kon et al. discussed a prolonged "setting phase" of the scapula representing a stabilization of the scapula to allow controlled humeral motion (Kon et al., 2008). It is argued that under load conditions the scapula is more fixed to the thorax to provide a stable base for the rotator cuff and enable adequate force transition (Kon et al., 2008). On the other hand, it is assumed that scapular kinematics presenting reduced scapular upward rotation, posterior tilt and external rotation diminish the subacromial space and thereby compress interposed tissues like in conditions of subacromial impingement (Michener et al., 2003). Whether the demonstrated scapular alterations in this study of increased upward rotation compromises scapular stability to allow for a sufficient subacromial space and on the other hand potentially reduces it by decreased posterior tilt and external rotation remains subject of debate. A beneficial or impairing impact of those patterns on efficient shoulder movements might further be discussed in relation to populations with increased overhead demands as well as increased prevalence of shoulder complains like overhead athletes or craftsmen. However, the link between scapular patterns with reduced posterior tilt and external rotation in maximal loaded movements and the development of shoulder complaints remains highly speculative. The present study could show that scapular kinematics adapt depending on the external load that is applied. For the evaluation of impaired scapular kinematics those physiological changes in response to load might present a possibility to detect individuals at risk for shoulder pathologies. Seitz et al. could show that overhead athletes with and without scapular dyskinesis differ in their scapular position when statically holding the arm at 90° flexion against gravity only and a non-elastic strap. Athletes with dyskinesis showed less upward rotation as well as less external rotation with maximal contractions (Seitz et al., 2015).

Some limitations of the present study should be considered. The findings are based on a small sample of asymptomatic individuals and thereby may not represent the entire physiological response to maximal load situations. Methodologically it has to be pointed out that the highly standardized isokinetic movement of shoulder flexion and extension deviates from upper extremity movements during daily life and might have restricted functional movement compensation strategies. The assessment of scapular kinematics based on a marker-setup even tough showing acceptable reliability for humeral positions up to 120° might be seen critical due to known skin movement artefacts.

5. Conclusion

Unloaded and maximal loaded scapular kinematics follow the common pattern of continuous scapular upward rotation, posterior tilt and external rotation during arm rising and a reversal of those movements during arm lowering in asymptomatic individuals. However, differences occurred in magnitude and progression and thereby showing increased scapular upward rotation during shoulder flexion and extension whereas posterior tilt and external rotation were decreased for maximal eccentric and concentric arm descents, respectively in comparison to unloaded shoulder movements. Load effects were further seen for the scapulohumeral rhythm with greater scapular involvement at lower humeral positions and increased scapular motion extent under maximal loaded shoulder movements. Magnitudes of averaged group changes resembled previously characterized differences between individuals with and without shoulder pathologies. Whether observed scapular movement patterns under maximal loaded shoulder movements constitute a potential risk for the development of shoulder complaints might be subject of future investigations.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jelekin.2021.102517.

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Monique Wochatz is a PhD candidate and research associate at the University Outpatient Clinic (Sports Medicine and Sports Orthopaedics) in Potsdam (Germany). Her research focuses on the biomechanical assessment of shoulder movements with a particular interest in scapular kinematics and neuromuscular activation pattern of scapular muscles under various load conditions.