Author/s:
Hik, F;Ackland, DC

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DR. DAVID CHARLES ACKLAND (Orcid ID : 0000-0002-0559-7569)

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THE MOMENT ARMS OF THE MUSCLES SPANNING THE GLENOHUMERAL JOINT: A SYSTEMATIC REVIEW

Freya Hik and David Ackland

Department of Biomedical Engineering, University of Melbourne, AUSTRALIA

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Address for correspondence:

David Ackland
Department of Biomedical Engineering
University of Melbourne
Victoria 3010
AUSTRALIA
Email: dackland@unimelb.edu.au

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ABSTRACT

The moment arm of a muscle represents its leverage or torque-producing capacity, and is indicative of the role of the muscle in joint actuation. The objective of this study was to undertake a systematic review of the moment arms of the major muscles spanning the glenohumeral joint during abduction, flexion and axial rotation. Moment arm data for the deltoid, pectoralis major, latissimus dorsi, teres major, supraspinatus, infraspinatus, subscapularis, and teres minor were reported when measured using the geometric and tendon excursion method. The anterior and middle regions of the deltoid had the largest moment arm values of all muscles during humeral elevation, and were important levers in both the coronal and scapular planes as well as during flexion. The pectoralis major, latissimus dorsi, and teres major had the largest antagonistic moment arms during humeral elevation, with each of these muscles exhibiting prominent leverage in shoulder adduction, and the latissimus dorsi and teres major also in extension. The rotator cuff muscles had the largest moment arms in axial rotation regardless of the axial position of the humerus. The supraspinatus had the most prominent moment arms during early abduction in both the coronal and scapular planes as well as in flexion. This systematic review shows that the rotator cuff muscles function as humeral rotators and weak humeral depressors or elevators, while the three sub-regions of the deltoid contribute substantially to humeral elevation throughout the whole range of humeral motion. The pectoralis major, latissimus dorsi, and teres major are significant shoulder depressors, with all three acting as prominent abduction antagonists. This study provides muscle moment arm data on

functionally relevant shoulder movements that are involved in tasks of daily living, including lifting and pushing. The results may be useful in quantifying shoulder muscle function during specific planes of movement, in designing and validating computational models of the shoulder, and in planning surgical procedures such as tendon transfer surgery.

INTRODUCTION

The moment arm of a muscle force is defined by the perpendicular distance between the muscle's line of action and the instantaneous center of rotation of the joint in which it spans, and represents the capacity of that muscle to exert a joint torque (Pandy 1999). A muscle's moment arm is indicative of the role of the muscle in joint actuation, since the moment arm magnitude is representative of muscle leverage about a joint, while the moment arm direction determines whether joint movement is associated with muscle shortening or lengthening (Ackland et al. 2010; Otis et al. 1994; Graichen et al. 2001; Dostal and Andrews 1981; Jensen and Davy 1975; Wood et al. 1989). Thus, a muscle with a positive moment arm through a given movement has agonistic function, while a negative moment arm is indicative of antagonist muscle function. Clinically, muscles with large moment arms have greater mechanical advantage and potential to generate joint torque, often functioning as prime movers, while muscles with smaller moment arms tend to exhibit stabilising function, such as intrinsic muscles (Liu et al. 1998; Graichen et al. 2001; An et al. 1984).

The two techniques employed extensively in derivation of muscle moment arm data are the geometric method and the tendon excursion method. The geometric method involves direct measurement of the perpendicular distance between the muscle's path and the joint center of rotation (Garner and Pandy 2001; Graichen et al. 2001; Greiner et al. 2013; Hamilton et al. 2015; Hamilton et al. 2013; Herrmann et al. 2011; Howell et al. 1986; Poppen and Walker 1978; Walker et al. 2016; De Wilde et al. 2002). This necessitates locating the muscle-tendon unit line of action relative to a functional or anatomical joint centre (see Supplementary Material). Since the geometric method is typically performed *in vivo* using data from imaging modalities such as x-ray, computed tomography (CT), or magnetic resonance imaging (MRI) (Ackland et al. 2008; An et al. 1984), it is most often employed for just a small number of joint configurations. Ultimately, the accuracy of the geometric method is limited by the reliability of joint center of rotation location identification, and correct estimation of the muscle's line of action (McGill and

Norman 1986). For example, the glenohumeral joint center is often approximated as the center of the humeral head, but the glenohumeral joint may translate by up to 7 mm during abduction and 12 mm during internal rotation (Werner et al. 2004), which may have a substantial impact on the muscle moment arms of the spanning muscles. The geometric method is thus commonly used for evaluating muscle moment arms in the intervertebral joints, which have a much smaller range of motion (McGill and Norman 1986; McGill et al. 1988; Suderman and Vasavada 2017; Dumas et al. 1991).

The tendon excursion method evaluates the moment arm quantity from the instantaneous gradient of the muscle-length versus joint-angle curve over a range of joint movement in a given plane (Supplementary Material) (Ackland and Pandy 2011). Unlike the geometric method, knowledge of the joint center location is not explicitly required in the calculation, and moment arms may be computed through a continuous range of joint motion (Ackland et al. 2008; Otis et al. 1994; Kuechle et al. 2000; Hughes et al. 1998; An et al. 1984). This approach lends itself well to *in vitro* measurements and computational simulations, since tendon excursion and joint angle data may be readily evaluated with relatively high accuracy (Ackland et al. 2008; Adams et al. 2007; Hughes et al. 1998; Kuechle et al. 1997; Kuechle et al. 2000; Liu et al. 1998; Liu et al. 1997; Nakajima et al. 1999; Schwartz et al. 2013; Otis et al. 1994).

Moment arms have been recorded for muscles spanning numerous joints in the human body including the neck, spine, ankle, knee, hip, fingers, wrist, elbow and shoulder (Kodek and Munih 2003; Ketchum et al. 1978; Lee et al. 2008; Delp et al. 1999; Krevolin et al. 2004) (McCullough et al. 2011; Jorgensen et al. 2001; Vasavada et al. 1998; Ackland et al. 2011). The objective of this study was to provide a systematic review of the moment arms of the major muscles and muscle sub-regions spanning the glenohumeral joint including those of the deltoid, pectoralis major, latissimus dorsi, teres major, and the rotator cuff muscles. Moment arm quantities were reviewed for functionally relevant shoulder movements including abduction in the scapular and coronal planes, flexion in the sagittal plane, and axial rotation in the neutral position. The data presented may be useful for evaluating the function of individual muscles, and for developing and validating computational models of the upper limb (Ackland et al. 2010; Pandy 1999).

METHODS

Literature Search Strategy

A literature search was conducted to identify previously published experimentally-derived moment arm data for the muscles spanning the glenohumeral joint. The study was conducted with reference to the guidelines outlined by the Preferred Reporting Items for Systematic Review and Meta-analysis (PRISMA) statement (Moher et al. 2010). The online database MEDLINE, via OVID, was systematically searched for English titles with no date restrictions. Keywords included shoulder, moment arm, glenohumeral joint, biomechanical model, mechanical advantage, and muscle line of action.

Selection criteria and quality assessment

An initial online search in Medline was performed with the following inclusion criteria: moment arm data reported for muscles spanning the glenohumeral joint including the deltoid, pectorals major, latissimus dorsi, supraspinatus, infraspinatus, teres minor, and subscapularis; moment arm data derived using geometric or tendon excursion methods; planes of motion included coronal plane abduction, scapular plane abduction, flexion, and axial rotation in the neutral position. Exclusion criteria included: Moment arm data reported for wheelchair propulsion, lifting or throwing activities, sports, or movements not described in the inclusion criteria; moment data for the pathological or non-native shoulder joint, including the prosthetic glenohumeral joint; moment arm data derived from non-human studies and from computational models. After removal of duplicates, full texts were retrieved. References of all full-text articles were then manually checked for other relevant titles.

The quality of each publication was quantified as described previously (Hart et al. 2016). Briefly, included studies were rated using a modified version of the Downs and Black checklist, with the modified version having a maximum score of 12 (Downs and Black 1998). A total score ≥ 9 indicated high methodological quality, a score of 6 to 8 indicated moderate quality, and a score ≤ 5 indicated low quality. Two reviewers (DCA and FCH) independently rated each study on the 12 item criteria and inter-rater disagreement was discussed in a consensus meeting.

Data analysis

Continuous muscle moment arm data as well as moment arm peaks were reported during coronal plane abduction, scaption, saggital-plane flexion and axial rotation of the glenohumeral joint. The plane of scaption was defined parallel to the scapular plane, and 30 degrees anterior to the coronal plane. All elevation movements assumed zero degrees of axial rotation. Moment arm data for axial rotation were included for internal and external rotation of the shoulder in the neutral position (approximately zero degrees of arm elevation), since data for this joint position are most widely reported. Each moment arm study was categorized according to technique (geometric or tendon excursion method).

RESULTS

Search Strategy, methodological quality and risk of bias

The initial literature search identified 34,805 titles, which was reduced down to 25,280 after the removal of duplicates (Figure 1). The full texts of 40 articles were retrieved after employing inclusion/exclusion criteria, with 16 articles meeting the selection criteria, and an additional four articles included, sourced from cited references in these articles (Table 1). The methodological quality scores ranged from 5 to 12 (of 12), with an average score of 9. There were 11 studies of high quality, 7 studies of moderate quality, and 2 studies of low quality. All 20 studies clearly described their main study outcome measures in either the Introduction or Methods sections. No other criteria from the quality assessment were met by all included articles.

Muscle moment arms, coronal plane abduction

The anterior deltoid, middle deltoid, supraspinatus, and infraspinatus had the largest abductor moment arms throughout coronal plane abduction, while the pectoralis major, latissimus dorsi, teres major, and subscapularis had the largest adductor moment arms. The posterior deltoid and teres minor had biphasic function and acted as either an abductor or adductor depending on the humeral position (Figure 2).

The abduction moment arm of the anterior deltoid increased with abduction angle, and had a peak value ranging between 26 mm and 30 mm at abduction angles greater than 90º (Ackland et al. 2008; Kuechle et al. 1997; Schwartz et al. 2013) (Figure 3); however, one high quality paper reported that the anterior deltoid was an adductor at low abduction angles and became and abductor beyond 45º of abduction, with a maximum abduction moment arm value of 60 mm at 90º of abduction (Walker et al. 2016). The mean maximum moment arm of the anterior deltoid was 36.2 ± 8.0 mm (n=4) (Table 2).

Three studies demonstrated that the middle deltoid had an abductor moment arm that increased with abduction angle, peaking close to the mid-range of motion with a mean magnitude of 26.8 ± 1.7 mm (Ackland et al. 2008; Kuechle et al. 1997; Walker et al. 2016). One high quality study reported a continuously increasing abductor moment arm for the middle deltoid throughout the entire range of abduction (Schwartz et al. 2013).

The latissimus dorsi was a prominent adductor, demonstrating antagonist function throughout abduction (Ackland et al. 2008; Kuechle et al. 1997). Its moment arm trends were parabolic through the range of abduction, with a mean maximum adductor moment arm magnitude of 37.3 ± 1.7 mm (n = 2) occurring beyond 69º of abduction

The abduction moment arm of the supraspinatus had a mean peak magnitude of 28.2 ± 1.6 mm (n = 3) in very early abduction, with the moment arm then tending to decrease with increasing abduction angle (Ackland et al. 2008; Kuechle et al. 1997; Liu et al. 1998) (Figure 2). In contrast, the subscapularis had an antagonistic moment arm that increased with increasing abduction angle, with a peak adductor moment arm occurring in mid-late abduction with a magnitude ranging between 7 mm and 13 mm. (Ackland et al. 2008; Kuechle et al. 1997; Herrmann et al. 2011; Greiner et al. 2013). One moderate quality study reported a peak adduction moment arm for the subscapularis of just 2 mm (Herrmann et al. 2011). The mean maximum moment arm of subscapularis was 8.1 ± 2.3 mm (n = 4).

The teres minor was an adductor in early-mid abduction and an abductor beyond 45º of abduction (Ackland et al. 2008; Greiner et al. 2013; Herrmann et al. 2011; Kuechle et al. 1997). It had a mean maximum abduction moment arm magnitude of 6.4 ± 2.6 mm (n = 4) at abduction angles greater than 60º. The teres major had large abductor moment arms increasing in early abduction to a peak of 49 mm, then steadily decreasing with abduction angle.

Muscle moment arms, scaption

The most substantial differences in elevation moment arms between the scapular- and coronal plane occurred for the subscapularis: this muscles was an adductor in the coronal plane and an abductor in the scapula plane (Figures 2 and 4). The teres minor acted as an abductor during scaption, but in the coronal plane at abduction angles less than 45º, this muscle was an adductor (Ackland et al. 2008; Greiner et al. 2013; Walker et al. 2016). The supraspinatus, infraspinatus, and three sub-regions of the deltoid had similar moment arm trends and maximum moment arm values in both scaption and coronal plane abduction.

The anterior deltoid, middle deltoid, supraspinatus, infraspinatus, subscapularis, and teres minor had the largest abduction moment arms during scaption, while the pectoralis major, latissimus dorsi and the teres major were the major adductors. The posterior deltoid had biphasic function, acting as an abductor or adductor depending on the humeral position (Figure 4).

The anterior deltoid had an abductor moment arm that increased with scaption angle, with a mean peak of 33.9 ± 5.0 mm (n = 5) (De Wilde et al. 2002; Liu et al. 1997; Poppen and Walker 1978; Kuechle et al. 1997) (Figure 5). The middle deltoid was also a large contributor to scaption and had a mean peak abductor moment arm of 33.4 ± 1.5 mm (n = 6) (Garner and Pandy 2001; Hamilton et al. 2015; Liu et al. 1997; Kuechle et al. 1997; De Wilde et al. 2002; Poppen and Walker 1978). All studies that reported moment arms of the posterior deltoid during scaption showed that this muscle acted as an adductor at low abduction angles and as an abductor in late abduction (Kuechle et al. 1997; De Wilde et al. 2002; Garner and Pandy 2001; Liu et al. 1997), with a mean peak abduction moment arm of 16.9 ± 4.8 mm (n = 6).

The supraspinatus was an abductor in the scapular plane, and had a mean maximum moment arm of 26.4 ± 1.3 mm (n = 10). Three medium quality studies and one high quality study demonstrated for the supraspinatus a relatively constant abductor moment arm throughout scaption (Otis et al. 1994; Howell et al. 1986; Poppen and Walker 1978; Graichen et al. 2001).

Muscle moment arms, flexion

The muscles with the largest flexion moment arms were the anterior deltoid, middle deltoid, pectoralis major, and supraspinatus, while the posterior deltoid, latissimus dorsi, teres minor, and teres major had the largest extensor moment arms (Figure 6). The peak flexor moment arm of the anterior deltoid was between 29 mm and 40 mm (Figure 7). Two high quality studies showed that its moment arm values decreased with increasing flexion angle, while another high quality study showed its moment arm increased with flexion angle (Kuechle et al. 1997; Schwartz et al. 2013; Ackland et al. 2008). Similarly, the middle deltoid had a large range of reported maximum flexor moment arm (12 and 28 mm) throughout the range of shoulder flexion. The mean peak extensor moment arm of the posterior deltoid was 36.4 ± 10.5 mm (n = 3). Maximum values occurred during early flexion, after which its moment arm decreased with increasing flexion (Ackland et al. 2008; Kuechle et al. 1997; Schwartz et al. 2013).

The flexor moment arm of the pectoralis major was greatest at 70° of flexion (21 mm), while the extensor moment arm of the latissimus dorsi peaked at 45° of flexion with reported values of 14 mm and 40 mm (Ackland et al. 2008; Kuechle et al. 1997). The teres major had the largest extensor moment arm, with Ackland et al. (2008) and Kuechle et al. (1997) reporting a moment arm peak of between 49 mm and 54 mm, respectively, occurring toward the mid-range of flexion.

The supraspinatus and subscapularis had a peak flexion moment arm of 43 mm and 23 mm, respectively (Ackland et al. 2008), while the teres minor was generally an extensor throughout flexion and had a peak moment arm of between 10 mm and 21 mm (Ackland et al. 2008; Greiner et al. 2013).

Muscle moment arms, axial rotation

The pectoralis major, latissimus dorsi, teres major, infraspinatus, and teres minor were external rotators in the neutrally aligned humerus, while the anterior deltoid, middle deltoid, posterior deltoid, supraspinatus, and subscapularis were internal rotators (figure 8).

The anterior deltoid was an external rotation agonist. It had internal rotation moment arm that increased with external rotation to a peak of 16 mm and 28 mm (Figure 9) (Kuechle et al. 2000; Schwartz et al. 2013). While one high quality study reported that the middle deltoid was an internal rotator during external rotation (Schwartz et al. 2013), a moderate quality study reported a negligible moment arm in this muscle through the range of axial rotation (Kuechle et al. 2000). One moderate quality study and one low quality study showed the posterior deltoid had an internal rotator moment arm throughout axial rotation (Kuechle et al. 2000; Hamilton et al. 2013); however, a high quality study suggested that the posterior deltoid acted as both an external and internal rotator, depending on the position of the externally rotated shoulder (Schwartz et al. 2013).

The infraspinatus was a prominent external rotator throughout axial rotation, and had a relatively constant moment arm between 20 mm and 26 mm (Adams et al. 2007; Kuechle et al. 2000; Hamilton et al. 2013). The mean maximum moment arm for this muscle was 24.5 ± 0.9 mm (n = 3). The subscapularis was an internal rotator during axial rotation, with a mean maximum moment arm of 20.6 ± 2.8 mm (n = 3) (Table 2) occurring during external rotation (Kuechle et al. 2000; Herrmann et al. 2011; Greiner et al. 2013). The teres minor was an internal rotator throughout axial rotation, with a relatively constant moment arm trend ranging between 17 mm and 25 mm (Adams et al. 2007; Kuechle et al. 2000; Hamilton et al. 2015; Greiner et al. 2013; Herrmann et al. 2011).

DISCUSSION

The objective of this study was to systematically review the literature for experimentally measured muscle moment arm data reported for shoulder abduction, flexion and axial rotation, which are motions commonly performed during activities of daily living including lifting, pushing, brushing hair, eating, as well as sporting activities (Khadilkar et al. 2014). While there was notable variation in moment arm magnitudes reported, even for the same muscles and joint positions, there was consensus that the anterior and middle deltoid had the greatest elevator leverage of all muscles, with the anterior deltoid the most prominent flexor, and the middle deltoid and anterior deltoid both the most significant elevators in scaption and coronal plane abduction. The subscapularis was an internal rotator, while the infraspinatus and teres minor were external rotators. In contrast, the supraspinatus had little leverage in axial rotation, but was a prominent elevator in early coronal plane abduction, scaption and flexion. The latissimus dorsi was a depressor in both coronal plane abduction, scaption and flexion, while the pectoralis major was a prominent depressor in abduction and scaption, and also a flexor.

The anterior and middle deltoid demonstrated large humeral torque capacity in elevation, and were relatively weak axial rotators. The anterior deltoid exhibited an increasing abductor and flexor moment arm with increasing humeral abduction and flexion angle, respectively, thus demonstrating greater leverage in the later stages of humeral elevation when more torque is required to lift the upper limb against its own weight. While the moment arms of the middle and anterior deltoid were similar in the coronal plane compared to those in the scapular plane, the posterior deltoid had more agonistic muscle function during coronal plane abduction compared to scaption, particular during mid- to late-elevation. Given that all three heads of deltoid are active during humeral elevation (Kronberg et al. 1990; Wattanaprakornkul et al. 2011), these results suggest greater combined leverage may be generated in the coronal plane, which may ultimately make lifting tasks with the upper limb more efficient in this plane.

The most prominent shoulder depressors were the pectoralis major, latissimus dorsi and teres major. In particular, the latissimus dorsi and teres major had large shoulder adductor and extensor moment arms, while the pectoralis major was a prominent adductor. The inferiorly directed lines of action of these muscles together with their insertions far from the glenohumeral joint centre of rotation (on the proximal humeral shaft) give these muscles exceptional depressor function and significant mechanical advantage during tasks requiring both humeral depression and internal rotation, such as climbing and swimming (Marchetti and Uchida 2011). In particular, the teres major, which is a frequently neglected muscle, has been shown from EMG data to play a significant role in shoulder function by being active as an antagonist and agonist during shoulder elevation and depression movements, respectively (Steenbrink et al. 2010; Marchetti and Uchida 2011). The results suggest that both the latissimus dorsi and teres major have greatest mechanical advantage during early to mid-range elevation in the coronal plane, scapular plane and saggital plane (between 30° and 50° of elevation), and may therefore be able to provide greater torque capacity with the upper limb in these shoulder joint configurations.

The results demonstrated that the subscapularis was an internal rotator, while the infraspinatus and teres minor were external rotators. Since these muscles are simultaneously activated during upper limb movement (Jenp et al. 1996), their opposing action forms a transverse plane force couple which ultimately generates compressive joint loading to stabilise the humeral head in the glenoid fossa (Jenp et al. 1996; Silldorff et al. 2014). The supraspinatus, while having less axial rotation leverage than the other rotator cuff muscles, was shown to have a large moment arm in early coronal plane abduction, scaption, and flexion. Since the deltoid sub-regions have relatively small moment arms at these joint positions, this prominent leverage of the supraspinatus suggests that it may behave as an initiator of upper limb elevation (Ackland et al. 2008). Ultimately, the frequent execution of arm elevation during activities of daily living, and the active role of the supraspinatus in generating the required torque, may contribute to supraspinatus tendon degeneration and tearing, which has greater prevalence than that of any other rotator cuff tendon (Steinbacher et al. 2010; Silldorff et al. 2014).

There are a number of limitations of this review that ought to be considered when interpreting the results. First, while there were no discernable differences in moment arm trends between the tendon excursion method and geometric method, these strategies present significant challenges in reproduction of single-degree-of-freedom joint motion and evaluation of joint rotation axes, respectively. Variability in joint centre location and joint angular motion may ultimately translate to moment arm errors in both the *in vivo* and *in vitro* setting. Second, some studies subdivided muscles into multiple sub-regions and their respective moment arms, since a number of broad and multi-pennate muscles have been shown to have different activation patterns across their muscle belly (O'Connell et al. 2006). To compare and pool datasets between different study designs, the moment arms for some muscles across their sub-regions, such as the pectoralis major, were averaged. Therefore, the reported average moment arm may not necessarily be representative of that of a functional sub-region. Finally, a number of studies did not normalise moment arms to specimen or subject size, or may have used cadaveric specimens from elderly subjects. This may result in moment arm errors and discrepancies with data expected in healthy young adults.

The studies examined in this review reported muscle moment arm data about specific joint motion axes in selected anatomical planes of upper limb motion (see Supplementary Material for details); however, activities of daily living and sports applications involve shoulder motion in a variety of joint motion planes not described in the literature. Notable gaps in the moment arm literature occur for shoulder hyperextension, hyperadduction, abduction and flexion beyond 120° of arm elevation, and horizontal flexion with the shoulder positioned at various elevation angles. Furthermore, muscles may contribute torque about multiple joint axes simultaneously for given shoulder position, for example, the anterior deltoid as both an elevator and an internal rotator. Despite the many varied shoulder joint positions and potential muscle lever effects, it is most practical in the experimental setting to evaluate moment arms in anatomical planes of motion, since bone orientations and joint motion can be readily delineated and reproduced. This review concludes that specific anatomical planes of shoulder motion which are consistently used in the literature for reporting of moment arm data ought to be adopted as standardised joint positions used in future moment arm studies. These include, but are not limited to, elevation and depression in the scapular plane, coronal plane and sagittal plane, as well as axial rotation of the humerus in its neutral position, and horizontal flexion with the upper limb in 90° of elevation. Validated anatomical shoulder models may serve as a useful tool for estimating moment arm data in non-anatomical shoulder positions, or for various upper limb configurations in the case of multi-joint spanning muscles.

The results from this study may be used in developing and validating anatomical musculoskeletal models of the upper limb, which have previously been used to assess individual muscle contributions to joint loading and stability, as well as to evaluate the biomechanical influence of surgical procedures such as tendon transfer and joint replacement surgery on muscle and joint function (Favre et al. 2010; Wu et al. 2016; de Witte et al. 2014; Ackland et al. 2010). For example, shoulder muscle forces, which are frequently used to quantify muscle function, may be estimated using musculoskeletal models and the principal that the sum of muscle forces and their respective moment arms about a given joint during a task is equal to the net joint moment. Ultimately, muscle force solutions must be determined computationally, since more muscles span the shoulder joint than the degrees of freedom of possible joint motion, and there is an infinite combination of possible muscle forces that may produce a joint torque.

In conclusion, the present study reports the function of the deltoid, latissimus dorsi, pectoralis major, teres major and rotator cuff muscles based on their moment arms during coronal plane abduction, scaption and axial rotation. The anterior and middle deltoid were the greatest humeral elevators, while the pectoralis major, latissimus dorsi and teres major were the most significant shoulder depressors. The rotator cuff muscles are responsible for both axial rotation and elevation of the humerus. The results of this study may be useful for classifying shoulder muscle function, and in developing musculoskeletal models for clinical and surgical applications.

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FIGURE CAPTIONS

Fig 1: Flow chart illustrating inclusion of studies in the present review.

Fig. 2: Moment arms of muscles spanning the glenohumeral joint during coronal plane abduction. Positive moment arm values indicate abduction while negative values indicate adduction. Moment arm units are millimetres. An asterisk indicates moment arm data that were averaged across two or more muscle sub-regions.

Fig. 3: Maximum moment arm values for muscles spanning the glenohumeral joint during coronal plane abduction. See caption of Figure 2.

Fig. 4: Moment arms of muscles spanning the glenohumeral joint during scaption (scapula plane abduction). See caption of Figure 2.

Fig. 5: Maximum moment arm values for muscles spanning the glenohumeral joint during scaption (scapula plane abduction). See caption of Figure 2.

Fig. 6: Moment arms of muscles spanning the glenohumeral joint during flexion in the sagittal plane. Positive moment arm values indicate flexion; negative values indicate extension. Moment arm units are millimetres. An asterisk indicates moment arm data that were averaged across two or more muscle sub-regions.

Fig. 7: Maximum moment arm values for muscles spanning the glenohumeral joint during flexion in the sagittal plane. See caption of Figure 6.

Fig. 8: Moment arm trends of muscles spanning the glenohumeral joint during axial rotation with the humerus in the neutral position. Positive joint angles indicate external rotation while negative angles represent internal rotation. A muscle with a positive moment arm externally rotates the humerus while a muscle with a negative moment arm internally rotates the humerus. Moment arm units are millimetres. An asterisk indicates moment arm data that were averaged across two or more muscle sub-regions.

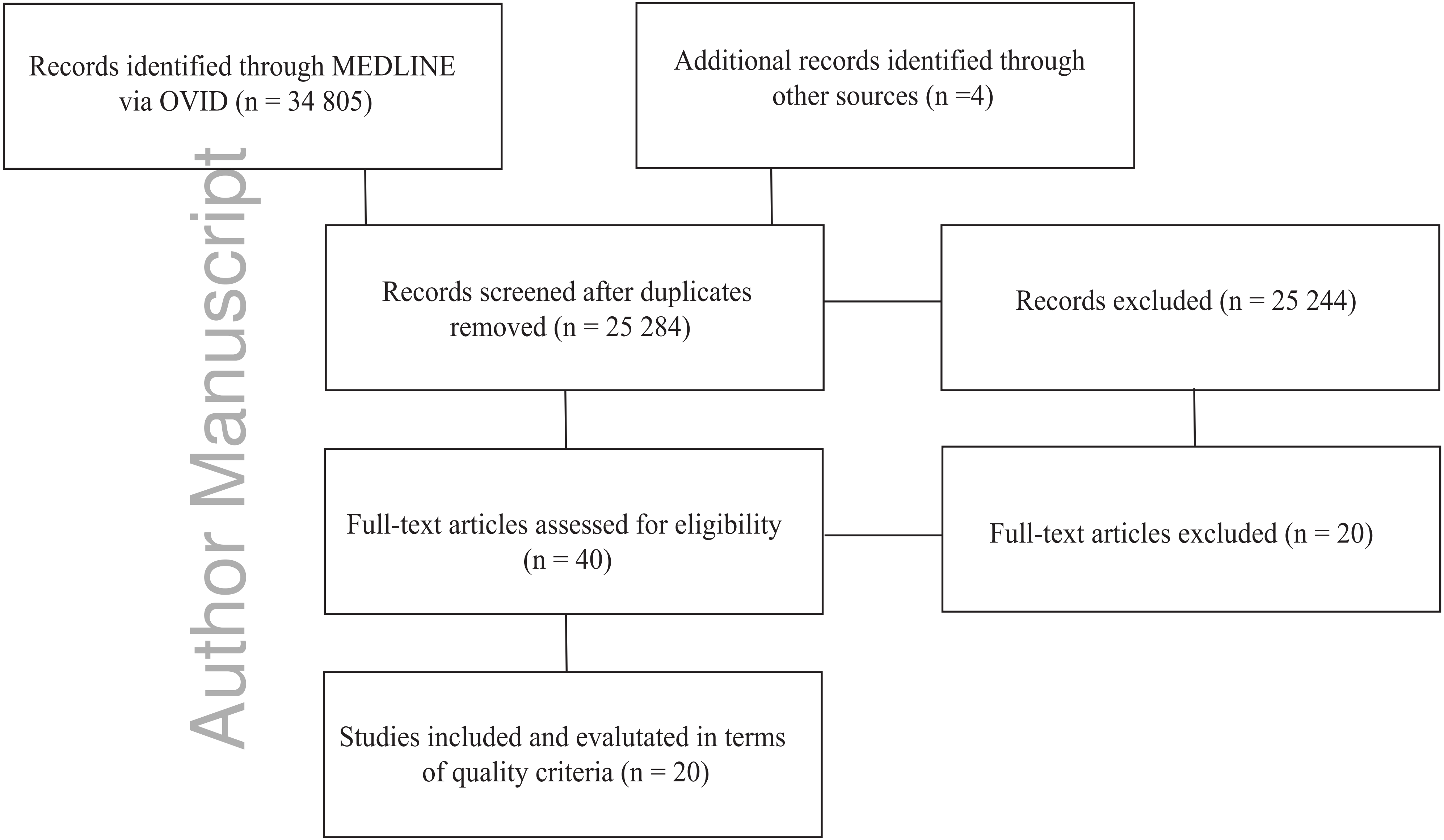
Fig. 9: Maximum moment arm values for muscles spanning the glenohumeral joint during axial rotation with the humerus in the neutral position. See caption of Figure 8.

Table 1: Details of studies included in the present review where applicable, including author, sample size, gender ratio, mean age and range, moment arm measurement method used (tendon excursion method or geometric method), study type (in vitro or in vivo), and quality rating based on the checklist of Downs and Black (1998).

Author	**Sample size (n)**	**Gender ratio (Male: Female)**	**Age (range)**	**Measurement method**	**Study type**	**Quality rating**
Ackland et al., 2008	8	4:04	87 (81-98)	Tendon excursion	In vitro	11
Adams et al., 2007	1			Tendon excursion	In vitro	6
De Wilde et al., 2002	65			Geometric	In vitro	9
Garner and Pandy, 2001	1	1:00	25	Geometric	In vitro	7
Graichen et al., 2001	10	4:06	(22-34)	Geometric	In vivo	11
Greiner et al., 2013	7		74 (61-82)	Geometric	In vitro	11
Hamilton et al., 2013	1			Geometric	In vitro	5
Hamilton et al., 2015	1			Geometric	In vitro	7
Herrman et at., 2011	7		77 (63-84)	Geometric	In vitro	8
Howell and Imobersteg, 1986	10	10:00		Geometric	In vivo	8
Hughes and Niebur, 1998	10	5:05	(40-89)	Tendon excursion	In vitro	12
Kuechle et al., 1997	12		59 (33-80)	Tendon excursion	In vitro	10
Kuechle et al., 2000	12		59 (33-80)	Tendon excursion	In vitro	8
Liu et al., 1997	10	4:05	67 (40-89)	Tendon excursion	In vitro	11
Liu et al., 1998	10	4:05	67 (40-89)	Tendon excursion	In vitro	11
Nakajima et al., 1999	10	4:05	67 (40-89)	Tendon excursion	In vitro	11
Otis et al., 1994	10		(70-80)	Tendon excursion	In vitro	7
Poppen and Walker, 1978	37			Geometric	In vivo	8
Schwartz et al., 2013	8	6:02	(46-68)	Tendon excursion	In vitro	9
Walker et al., 2016	12			Geometric	In vivo	9

Table 2: Average muscle maximum moment arms and standard error values for shoulder muscles calculated across all relevant studies for coronal-plane abduction, scapula plane abduction, flexion and axial rotation. Axial rotation data are provided for humerus in its neutral position. All data are given in mm.

	Coronal plane abduction		Scapular plane abduction		Flexion		Axial rotation	
	Moment arm	Standard error	Moment arm	Standard error	Moment arm	Standard error	Moment arm	Standard error
Anterior deltoid	36.2	8.0	33.9	5.0	35.5	3.3	-22.2	6.2
Middle deltoid	26.8	1.7	33.4	1.5	21.5	4.8	-14.6	12.6
Posterior deltoid	14.5	6.2	-16.9	4.8	-36.4	10.5	-7.3	1.3
Pectoralis major	-44.0	11.1	35.1	4.9	21.1	0.9	20.0	
Latissimus dorsi	-37.3	1.7	-35.6	8.4	-26.8	13.2	9.0	
Teres major	-47.6	1.5	-51.7	4.4	-51.7	2.7	7.5	
Supraspinatus	28.2	1.6	26.4	1.3	27.1	15.6	-4.0	
Infraspinatus	15.6	3.4	11.2	2.4	7.1	4.1	24.5	0.9
Subscapularis	-8.1	2.3	9.7	0.8	9.5	4.7	-20.6	2.8
Teres minor	6.4	2.6	8.5	6.5	-14.8	1.8	20.9	1.6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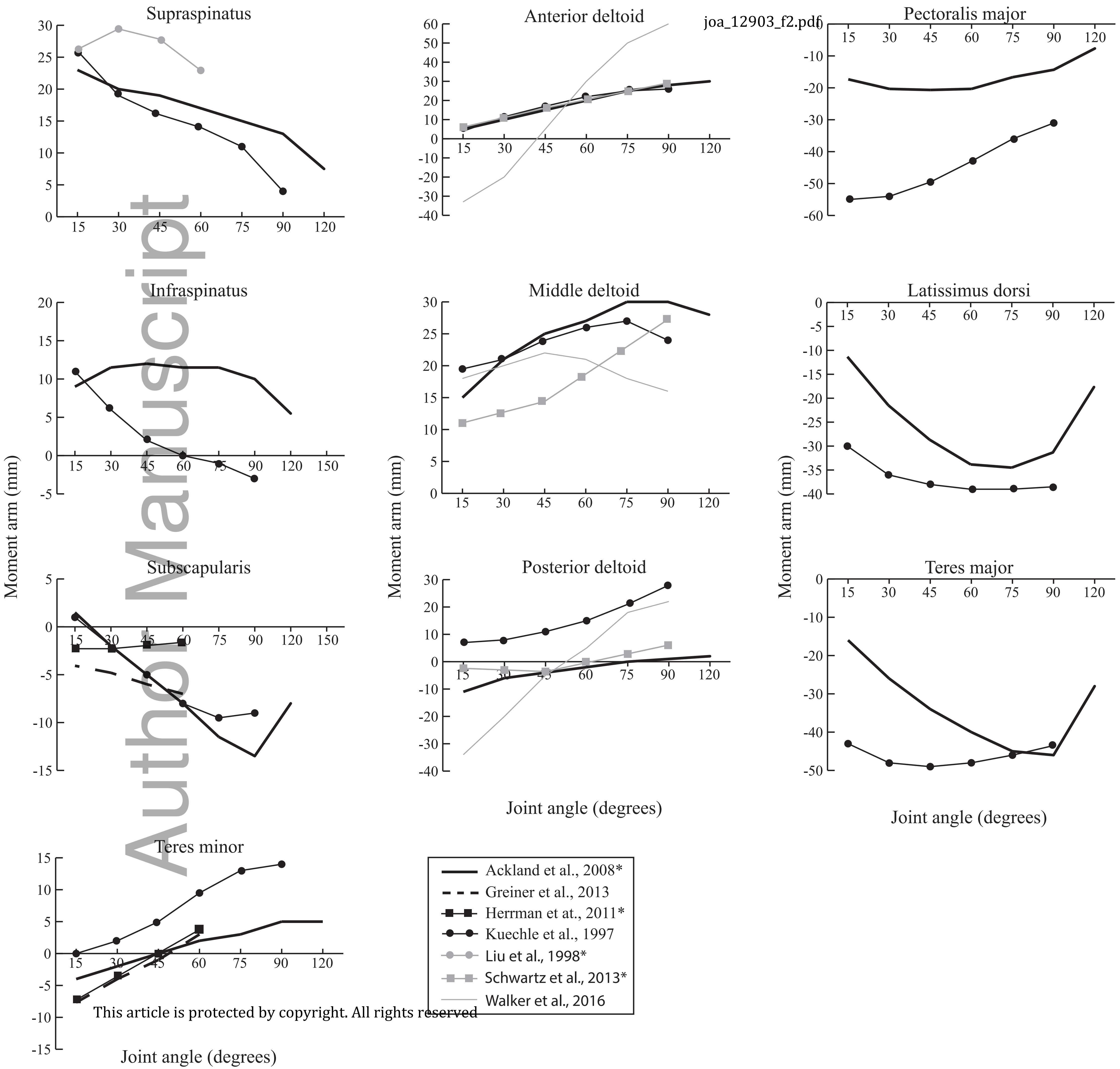
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Infraspinatus
Middle deltoid
Latissimus dorsi
Subscapularis
Posterior deltoid
Teres major
Teres minor
Moment arm (mm)
Joint angle (degrees)
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Ackland et al., 2008*
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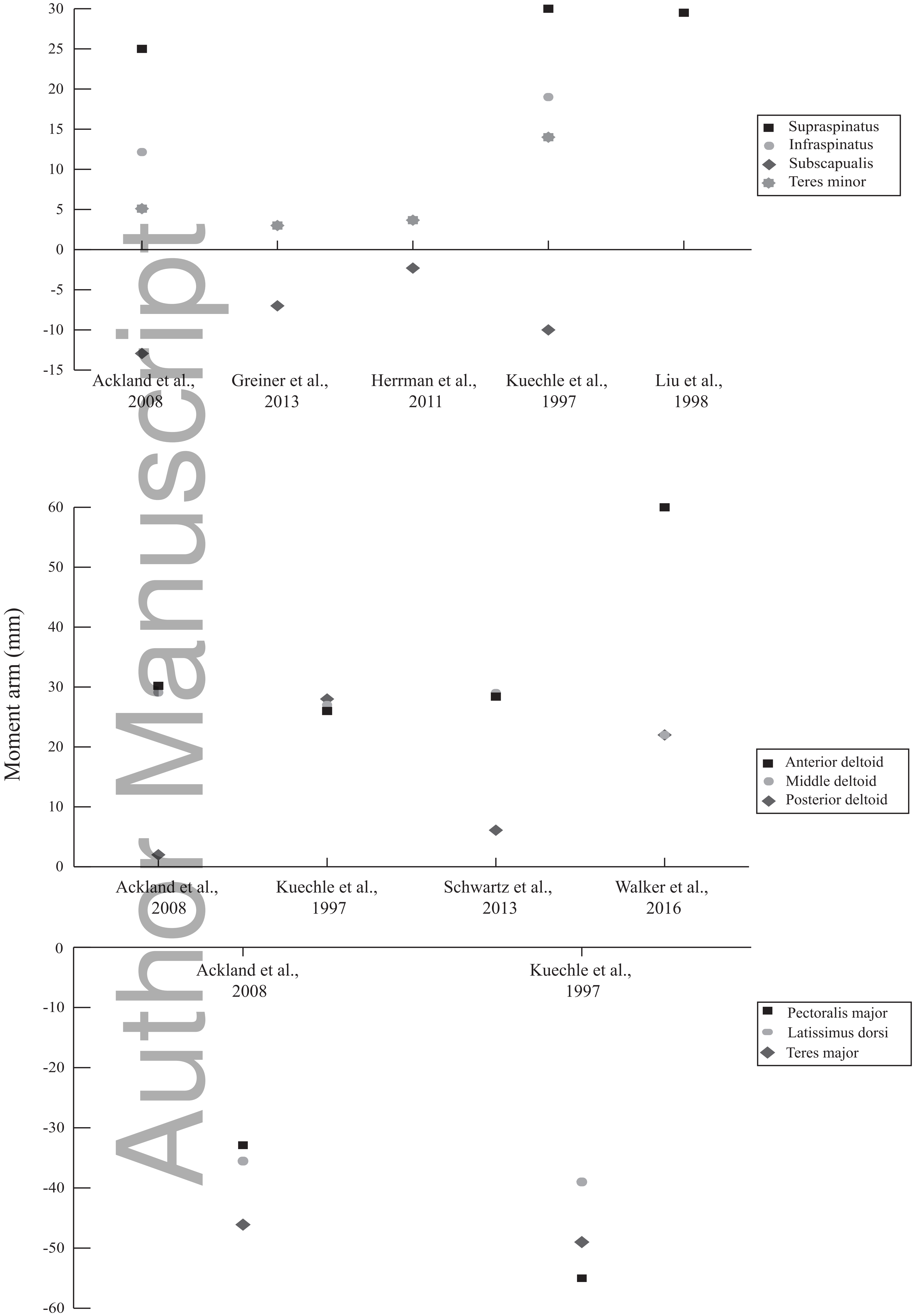
Herrman et at., 2011*
Kuechle et al., 1997
Liu et al., 1998*
Schwartz et al., 2013*
Walker et al., 2016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Ackland et al., 2008
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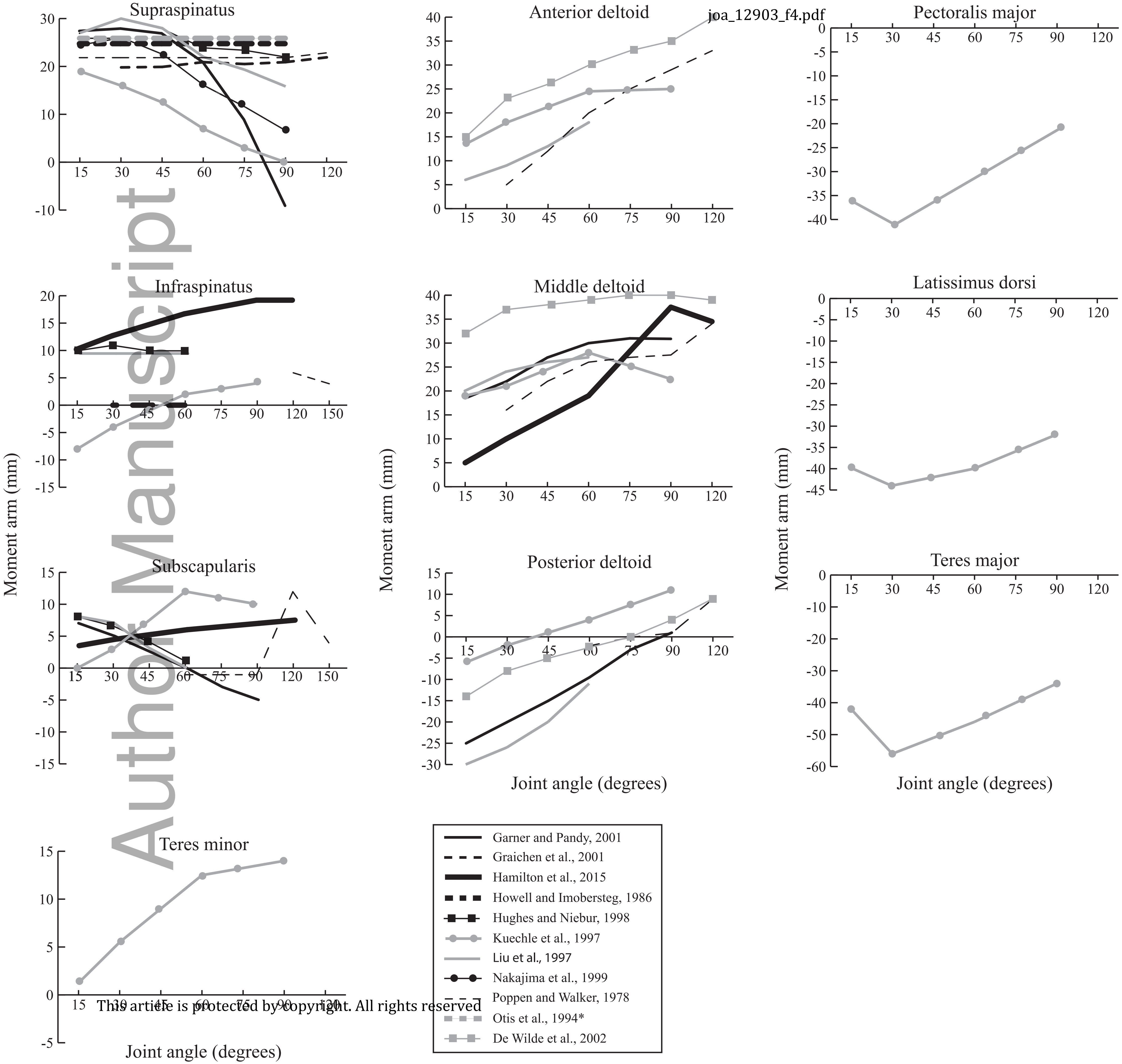

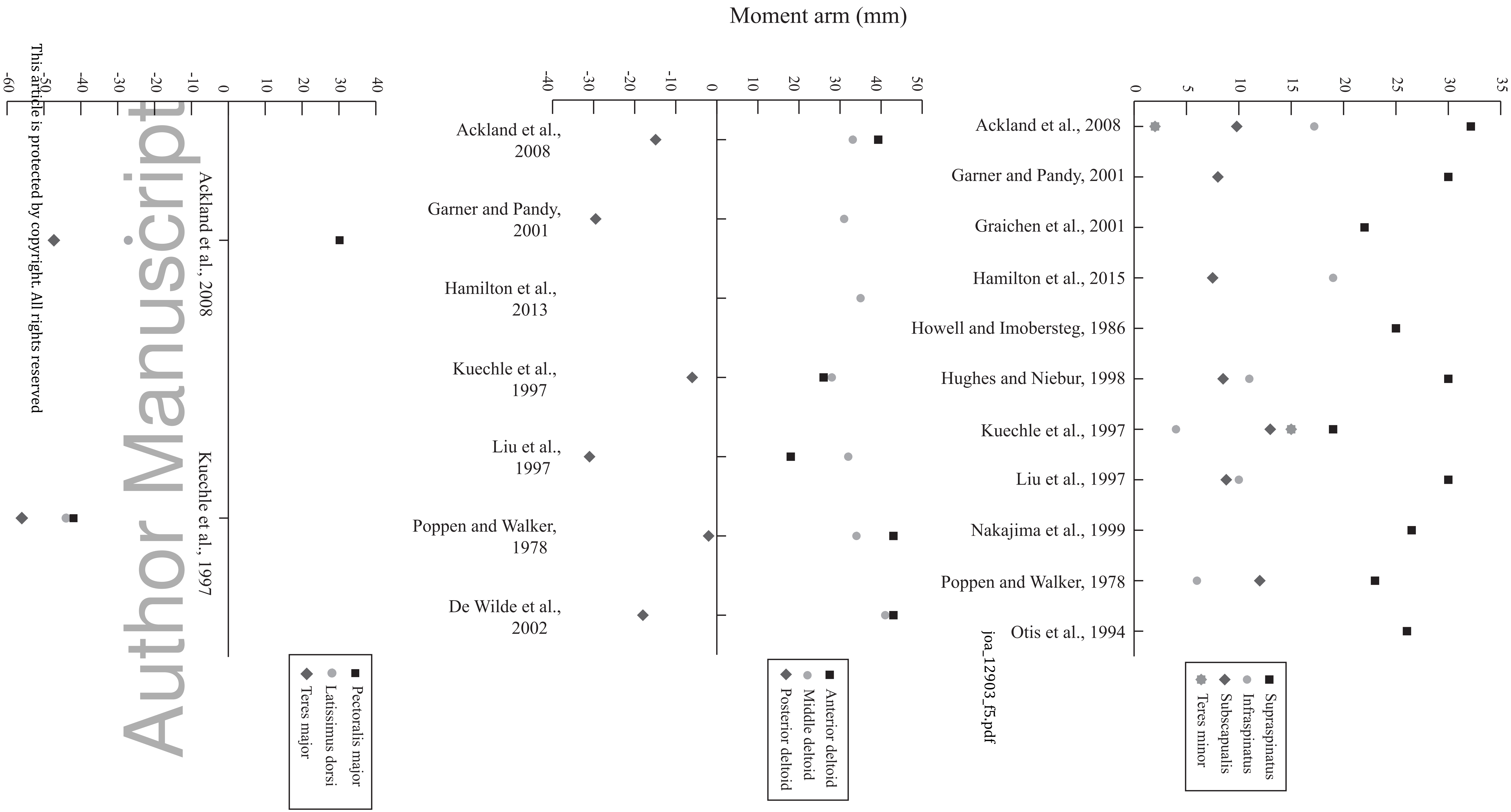

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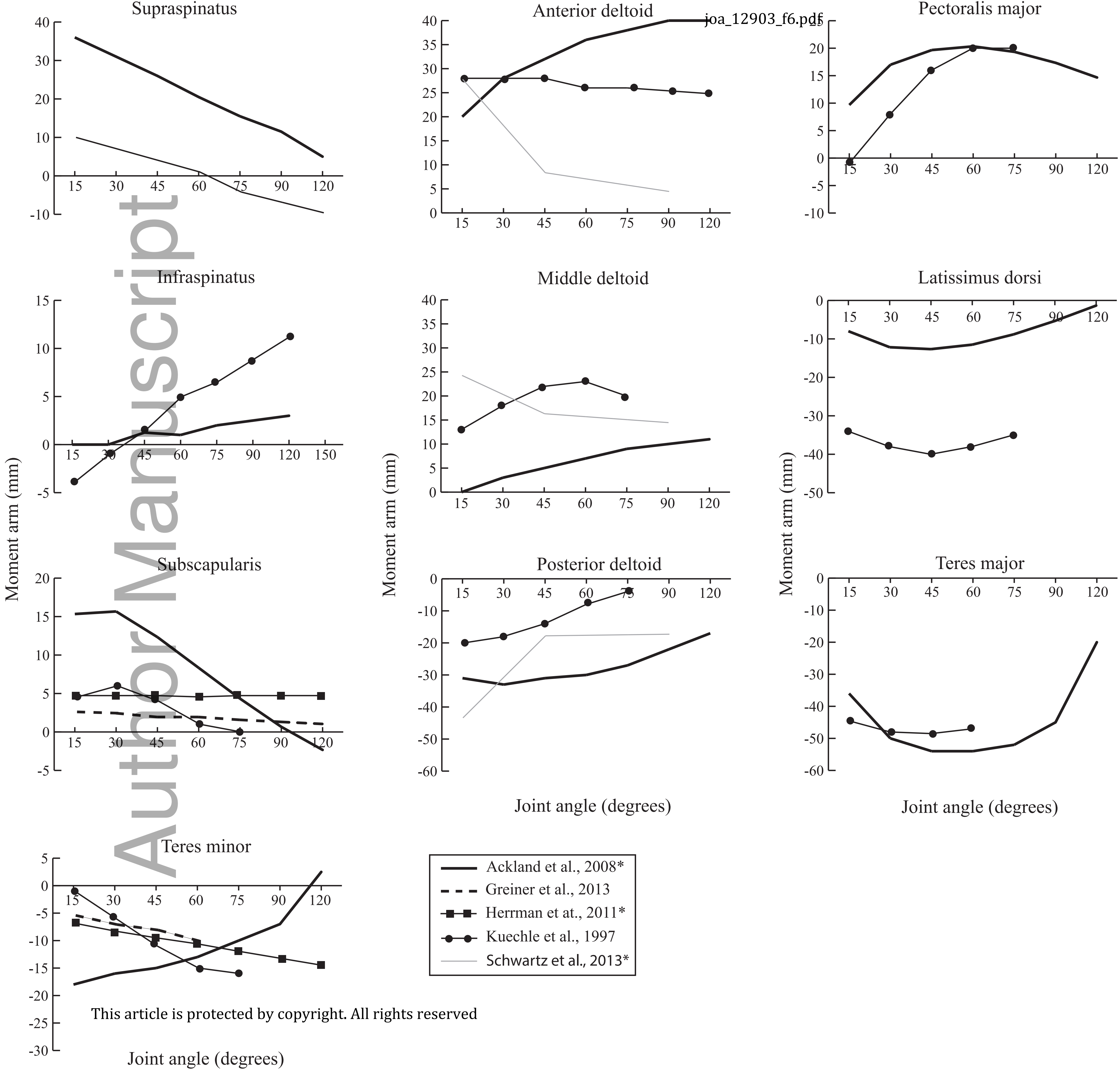
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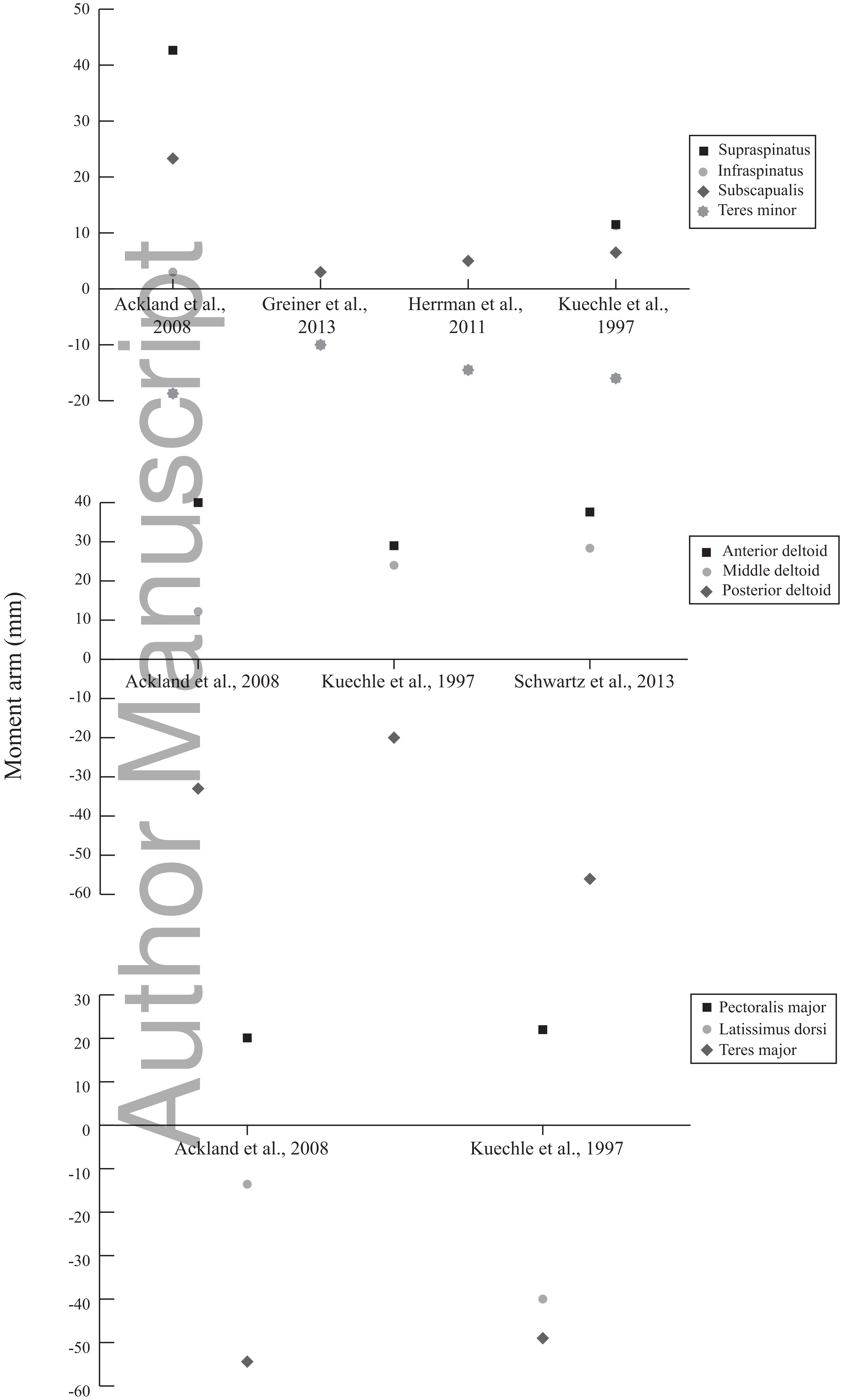
Schwartz et al., 2013*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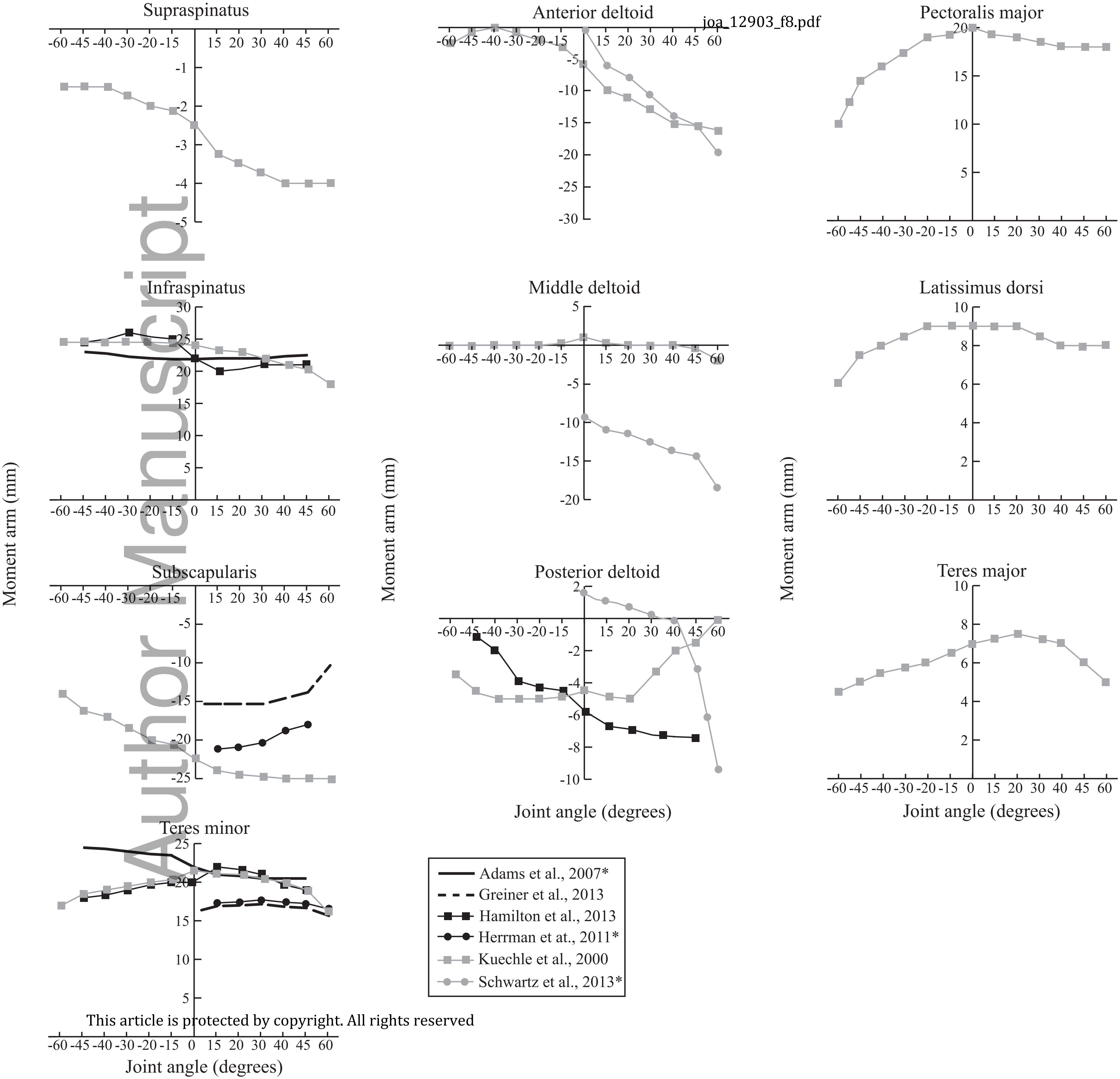
◆ Teres major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Joint angle (degrees)
Joint angle (degrees)
Joint angle (degrees)
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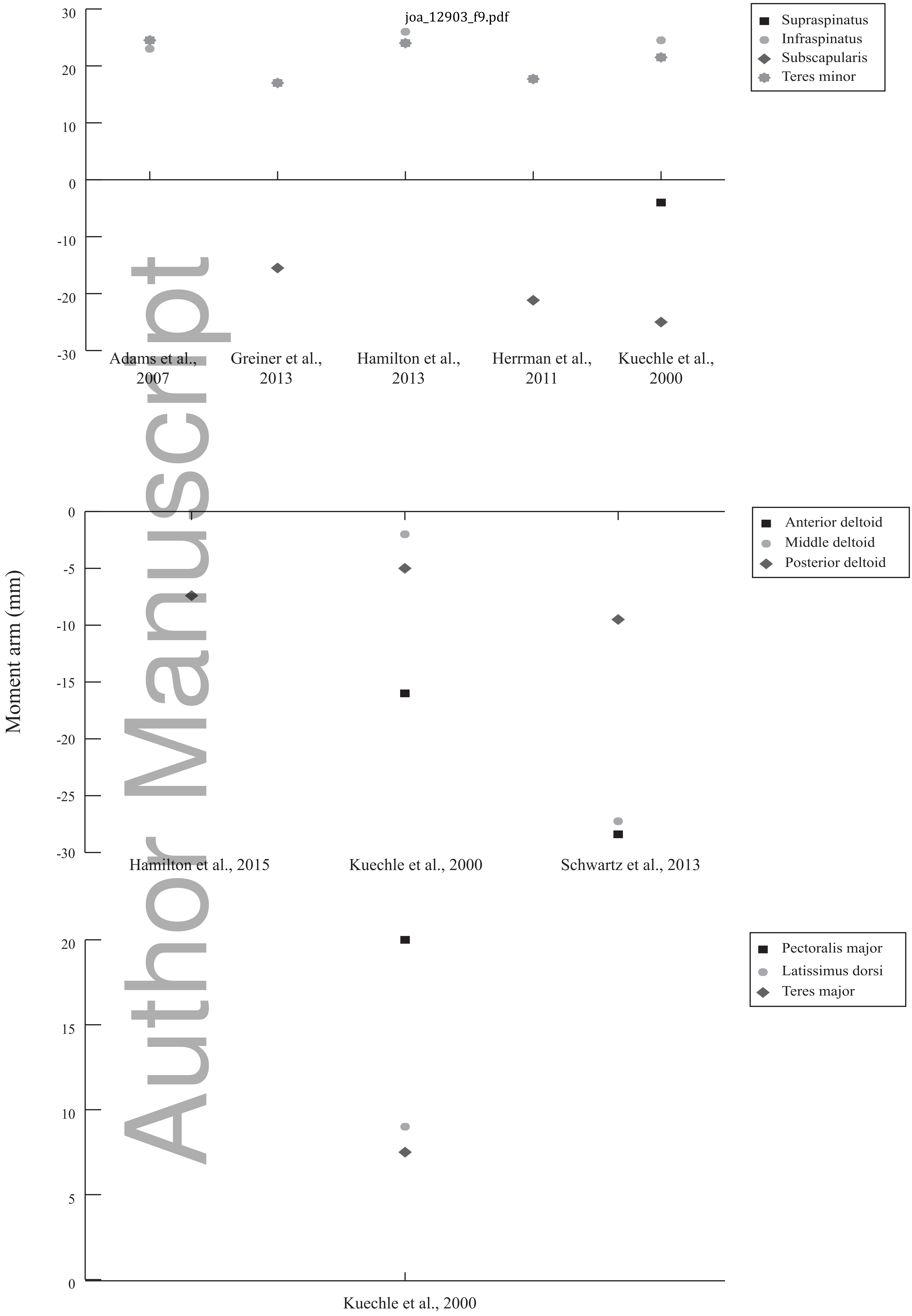
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