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# Anatomy and biomechanics of psoas major

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**Summary**

The fascicular anatomy of the psoas major was determined by dissection in three cadavers. Its actions on the lumbar spine in the sagittal plane were modelled on erect, flexion, and extension radiographs of ten adult males. Calculations revealed that psoas exerts only very small moments that tend to extend the upper lumbar spine and to flex the lower lumbar spine, but at maximum contraction the psoas exerts severe compression forces on the lumbar segments, and large shear forces.

**Relevance**

The results deny any substantial role of psoas as a flexor or extensor of the lumbar spine but reveal that activities involving psoas exert large compression and shear loads on the lumbar joints.

Key words: Lumbar vertebra, muscles, biomechanics, psoas major

## Introduction

The psoas major is well known as a flexor of the hip[1,2], but unlike any other muscle of the lower limb, the psoas arises from the lumbar spine. This feature implies that if the lower limb was fixed, as for example, in the standing position or in the exercise of sit-ups, psoas could have an action on the lumbar spine.

Electromyography studies show that the psoas is active during upright standing and during forward bending and lifting[3,4]. These observations prompted the inference that psoas major might function as a 'stabilizer' of the lumbar spine[3,4]. Others have proposed that psoas controls the lumbar lordosis[5] and balances the bodyweight in relaxed upright standing[6]. However, electromyography is limited in its power to define the actions or functions of a muscle. It shows only that the muscle is active during a movement, but it does not reveal the force exerted, or whether the muscle is generating the movement or is exerting some other action. Moreover, single-electrode studies do not reveal what effect a large muscle like psoas major has on each and every segment of the lumbar spine to which it is attached. Yet, such information is necessary if one is to appreciate what effect exercises involving the psoas have on either the normal or impaired lumbar spine.

To determine the segmental actions of a muscle certain items of information are required. The exact sites of attachment must be known, together with the lines of action of the muscle with respect to each and every joint that it crosses, and the relative size of the fibres acting on each joint. In the case of psoas major, textbook descriptions do not provide sufficient detail to enable this type of information to be derived with any certainty. The present study was therefore undertaken to determine the segmental morphology of the psoas major in order to explore its actions on the lumbar spine.

## Methods

The study was undertaken in two phases. First the morphology of the psoas major was determined by dissection. Subsequently its actions were modelled on flexion–extension radiographs of the lumbar spine.

### *Morphology*

The morphology of the psoas major was studied by dissection bilaterally in three embalmed, human adult

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male cadavers of donors aged in excess of 60 years. In each cadaver the muscle belly of psoas major was isolated by resecting the abdominal contents and the quadratus lumborum muscle. The iliopsoas tendon was isolated by removing the anterior muscles of the thigh. Upon stripping the iliacus piecemeal from its attachments to the ilium and to the iliopsoas tendon, the tendon was left with only psoas major attached to it. The tendon was then transected caudal to the lowest attachment of any fleshy fibres of the psoas major. This enabled the belly of psoas major to be stripped systematically.

Starting with the fibres with the most rostral and most anterior attachments to the vertebral column, small bundles of muscle fibres were gathered with forceps, detached from the vertebral column, and stripped caudally. As each bundle of muscle fibres was stripped, its tendons were peeled from the belly and main tendon of psoas major, and a note was made of their disposition and attachments. The sites of attachment of the resected bundles were recorded on tracings of anterior and lateral radiographs of a lumbar vertebral column.

Once resected, each bundle was trimmed of any tendinous fibres leaving only a bundle of fleshy, muscle fibres. The length of this bundle was measured with a rule to the nearest 0.5 cm, and its volume was measured to the nearest 0.5 ml by immersing it in a volumetric cylinder filled with water and recording the fluid displacement. These two measures for each bundle were used to calculate its physiological cross-sectional area (volume divided by length).

Once all six muscles had been totally resected, their sites of attachment were reproduced on a single tracing of a lateral radiograph of the lumbar spine to produce a composite map of attachment sites. This map depicted what could be construed as the fascicular anatomy of psoas major. A fascicle was defined as a group of muscle fibres that shared a common, discrete area of attachment on the vertebral column that was discontinuous from other areas of attachment, and which differed from other areas in terms of the vertebra or parts of the vertebra to which it was attached.

### *Biomechanics*

The possible actions of psoas major were modelled by plotting the attachments and lines of action of its component fascicles on tracings of anteroposterior and lateral radiographs of ten normal subjects in the erect, fully flexed, and fully extended postures of the lumbar spine. These latter movements had been executed with the pelvis clamped in the upright standing position, and so constituted lumbar motion in the absence of hip movement. The radiographs used were those described and used in previous studies of the movements of the lumbar spine using biplanar radiography[7]. The location of the instantaneous axes of rotation of each segment for every individual had also been determined in a previous study[8] and were recorded on the tracings.

The vertebral attachments of every fascicle of psoas major were marked as points on the tracings. The points used corresponded to the centroid of the area of attachment of each fascicle as recorded on the composite map constructed during the morphology phase of the present study. To establish the line of action of each fascicle, a line was drawn from its vertebral attachment site to a common point that marked the location of the iliopsoas tendon. This latter point was plotted immediately anterior to the iliopubic eminence: the site where the iliopsoas tendon leaves the abdominal cavity and curves posteriorly towards the lesser trochanter. Such lines of action were constructed for every fascicle on each of the tracings of the erect, flexion, and extension views of each of the ten subjects.

For the erect posture, the following parameters were measured or calculated for each fascicle in each of the ten subjects – the length of the moment arm at each segment crossed by the fascicle, the distance between its origin and the iliopubic eminence, the orientation of the fascicle, the maximum force exerted by the fascicle in the sagittal plane, and the moment, compression force, and shear force exerted on each segment. The present study was restricted to considering actions of the psoas major only in the sagittal plane because the locations of the axes of rotation for lateral flexion of the lumbar spine are not known with any certainty. Consequently, lateral bending moments could not be determined.

Moment arms were measured from the tracings as the perpendicular distance between the line of action of the fascicle and the instantaneous axis of rotation for each segment that the fascicle crossed. The direct measurements obtained from the radiographs were corrected for magnification due to divergence of the X-ray beam used to obtain the radiographs (a factor of 1.62). Moment arms acting in front of an axis of rotation so as to cause flexion were recorded as positive, and moment arms behind the axis of rotation so as to cause extension were recorded as negative.

The distance between the origin of each fascicle and the iliopubic eminence was measured directly from the tracings of the lateral radiographs and corrected for magnification to obtain a true projected length. This measure was used subsequently to determine the orientation of the fascicle and to calculate changes in length of the fascicle following flexion or extension of the lumbar spine.

The orientation of each fascicle was determined using the geometrical relationships depicted in Figure 1. For a given fascicle with an origin at O and an insertion into the psoas tendon at I, the fascicle exerts a maximum force ($F_{max}$) represented by the interval OI. The projection of I in the sagittal plane is P, and the interval OP represents the force exerted by the fascicle in the sagittal plane ($F_{sag}$). OP can be measured from lateral radiographs on which P and O have been marked. The interval PI represents the lateral displacement of the insertion of the fascicle and the

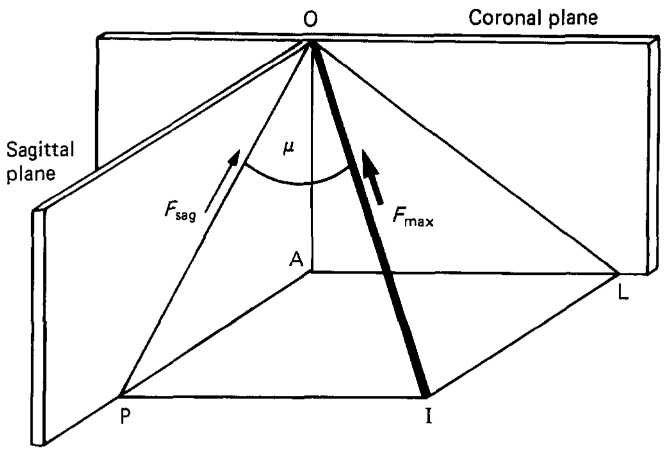


**Figure 1.** Graphical representation of a muscle fascicle orientated obliquely in three dimensions and the projections of its orientation in the sagittal and coronal planes. With an origin from the vertebral column at O and an insertion into the psoas tendon at I, the fascicle exerts a maximum force ($F_{max}$) represented by OI. The projection of I in the sagittal plane is P, which constitutes the site of insertion as seen in lateral radiographs. The projection of I in the coronal plane is L, which constitutes the site of insertion as seen in anteroposterior radiographs. The interval OP represents the force exerted by the fascicle in the sagittal plane ($F_{sag}$). The angle $\mu$ is formed between the intervals OP and OI in the triangle POI.

projection of I in the coronal plane is L. The magnitude of PI is equal to that of AL which can be measured from anteroposterior radiographs on which O and L have been marked.

If $\mu$ is the angle POI, $F_{max}$ and $F_{sag}$ are related by the equation

$$F_{sag} = F_{max} \cos \mu \qquad (1)$$

A representative value of the angle $\mu$ for every fascicle was determined using the relationship.

$$\tan \mu = \text{mean PI/mean OP} \qquad (2)$$

Where mean PI and mean OP were the mean values respectively of the length and lateral displacement of the fascicle in question as determined from the plots of the fascicle on the radiographs of each of the ten subjects.

For every fascicle, its maximum force of contraction was expressed as a function of the mean physiological cross-sectional area (PCSA) for that fascicle as determined in the morphological phase of the present study. The force was expressed in the form $F_{max}$ = PCSA × K, where K is a force coefficient with the units N $cm^{-2}$. For muscles in general, the value of K is believed to lie in the range 30–90 N $cm^{-2}$ [6, 9–12], but the value that applies specifically to psoas major has not been determined. Consequently, for the purposes of the present study, K was treated as an unknown. This precluded calculating the absolute magnitude of the force of any fascicle but nevertheless allowed the relative forces exerted by any fascicle or on any segment to be assessed.

By combining the representative angle $\mu$ for each fascicle with its representative force ($F_{max}$) the representative force it exerted in the sagittal plane ($F_{sag}$) could be calculated using equations (1) and (2).

The compressive force ($F_c$) exerted in the sagittal plane by the fascicle on its vertebra of origin is given by the equation

$$F_c = F_{sag} \sin \lambda \qquad (3)$$

Where $\lambda$ is the angle between the line of action of the fascicle in the sagittal plane and the transverse plane of the vertebra to which it is attached (Figure 2). Similarly, the shear force ($F_s$) exerted by the fascicle is given by the equation

$$F_s = F_{sag} \cos \lambda \qquad (4)$$

To determine the value of $\lambda$ for each fascicle at each segment, lines were drawn on the tracings of the lateral radiographs of each subject through the inferior vertebral end-plate of each lumbar vertebra to represent the transverse plane of each vertebra. The angle formed between each of these lines and the line

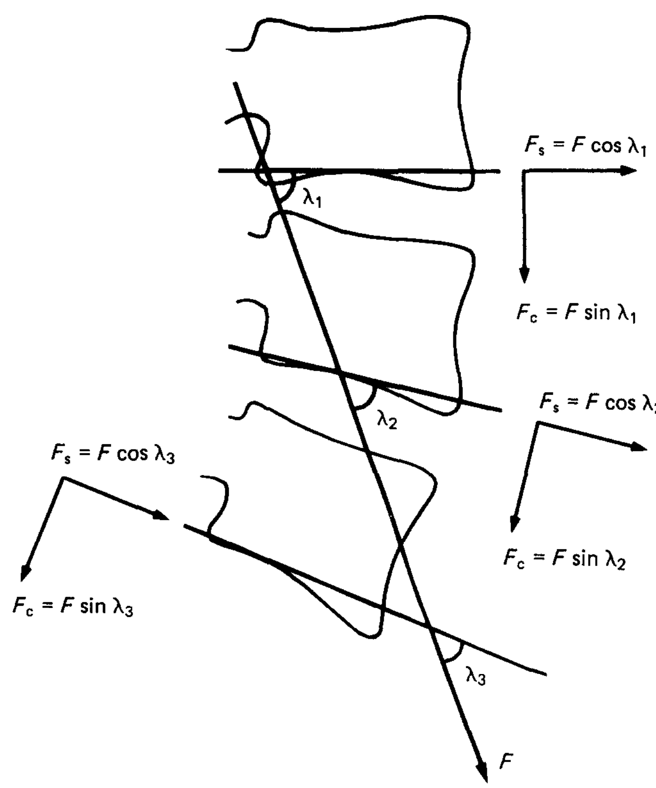


**Figure 2.** Sketch of a lateral view of three lumbar vertebrae crossed by a single fascicle of psoas major which exerts a force in the sagittal plane ($F_{sag}$). Lines drawn through the inferior end-plates of the vertebrae depict the transverse plane of the vertebra. The angle formed between the transverse lines and the line of action of the fascicle can be used to resolve the force of the fascicle into compression forces ($F_c$) and shear forces ($F_s$).

of action of any fascicle that crossed it was measured in all ten subjects. A representative value of $\lambda$ for each fascicle at each segmental level was determined by averaging the values of $\lambda$ for that fascicle and segment as measured in the lateral radiographs of the ten subjects studied. By combining this representative value and the representative value of $F_{sag}$ for each fascicle, the representative values of the compression and shear forces of the fascicle were derived using Equations (2) and (3).

Representative values of the moments exerted by each fascicle at each segment were calculated by combining the representative value of $F_{sag}$ for that fascicle with the mean value of the moment arm at each segment as measured from the lateral radiographs of the ten subjects studied.

To determine the possible actions of psoas as a flexor and extensor of the lumbar spine, its fascicles were plotted on the flexion and extension radiographs of the same ten subjects used for the erect posture. Using the same techniques as for the erect posture, the lines of action of the fascicles were determined along with their moment arms. The representative moments exerted by each fascicle were calculated as the product of the representative force exerted by each fascicle in the sagittal plane ($F_{sag}$) and the mean moment arm for each fascicle at each segment that it crossed. The change in length undergone by each fascicle in either flexion or extension was determined by subtracting the distance from its origin to the iliopubic eminence in the flexion or extension posture from the corresponding distance in the erect posture, all lengths having been corrected for magnification on the radiographs. After measuring the orientation of each fascicle with respect to the long axis of each vertebra, compression and shear forces for each segment were calculated as for the erect posture.

## Results

### *Morphology*

Inspection of the intact psoas major suggests that it is a homogeneous muscle with a continuous attachment to the vertebral column at one end, tapering to a single, round tendon at the other end. Dissection, however, reveals that the muscle consists of a series of overlapping segmental fascicles.

Each fascicle consists of bundles of fleshy fibres that arise from a discrete area on the lumbar vertebral column centred on either an intervertebral disc or a transverse process. Five fascicles arise from the $T_{12}$–$L_1$ to $L_4$–$L_5$ discs and five fascicles arise from the $L_1$–$L_5$ transverse processes. Additionally a fascicle arises irregularly from the $L_5$ vertebral body.

At each segmental level, those fascicles centred on the intervertebral disc were found to arise from the posterior seven-eighths or so of the lateral surface of the disc (extending as far posteriorly as the intervertebral foramen) and from the lateral surfaces of the vertebral bodies immediately above and below the disc (Figure 3). Those fascicles from the $L_1$–$L_2$ to

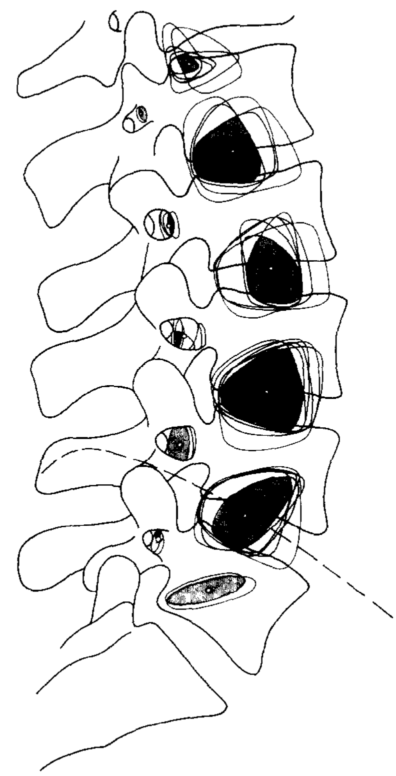

**Figure 3.** Sites of attachment of the fascicles of psoas major. The areas of attachment for each fascicle as seen in six specimens have been superimposed to determine the extent of variation and the areas consistently shared by all specimens (represented by the darker shading). The centroid of this latter area (white dot) was adopted for biomechanical purposes as the representative point of attachment of the fascicle.

$L_4$–$L_5$ discs were centred just posterior to the midpoint of the disc as seen in a lateral view. The fascicle from $T_{12}$ to $L_1$ extended more onto the $L_1$ vertebral body than to $T_{12}$ and was centred over the upper, posterior, lateral corner of $L_1$ (Figure 3).

The fascicles from the $L_3$ to $L_5$ transverse processes occupied the medial three-quarters or so of the anterior surface of the transverse process while the fascicles from $L_2$ and $L_1$ occupied only the medial one-quarter of the transverse process. The fascicle from the $L_5$ vertebral body, when present, arose from an obliquely set area on the lateral surface of the $L_5$ vertebral body extending upwards and forwards from the posterior, inferior corner of that surface (Figure 3).

Fascicles from the $L_1$–$L_2$ to $L_4$–$L_5$ discs and from the $L_1$ vertebral body were regularly present, as were fascicles from the $L_3$ and $L_4$ transverse processes. Fascicles from the $L_1$, $L_2$, and $L_5$ transverse processes were missing unilaterally in one or two specimens. The fascicle from the $L_5$ vertebral body was the least constant, being found in only three muscles in two specimens (Table 1).

The fibres in each fascicle passed caudally and slightly laterally to join the tendon of psoas major. As measured from their point of origin to where they become tendinous, the fleshy fibres of each fascicle were remarkably similar in length. Within the same specimen the fibres had the same length (to within

**Table 1.** Morphometric data on the fascicles of psoas major detailing their prevalence (*n*) in six muscles in three cadavers, their volumes, lengths, and physiological cross-sectional areas (PCSA)

| Fascicle | n | Volume (ml) | | Length (cm) | | PCSA ($cm^{-2}$) | |
|---|---|---|---|---|---|---|---|
| | | Mean | SD | Mean | SD | Mean | SD |
| $L_1$ VB | 6 | 28.4 | 6.3 | 13.7 | 1.4 | 2.11 | 0.56 |
| $L_1$ TP | 4 | 8.6 | 1.6 | 14.0 | 1.4 | 0.61 | 0.15 |
| $L_1$–$L_2$ IVD | 6 | 29.1 | 10.2 | 13.7 | 1.4 | 2.11 | 0.61 |
| $L_2$ TP | 5 | 13.9 | 6.9 | 13.4 | 1.3 | 1.01 | 0.45 |
| $L_2$–$L_3$ IVD | 6 | 22.1 | 5.9 | 13.7 | 1.4 | 1.61 | 0.35 |
| $L_3$ TP | 6 | 24.2 | 9.2 | 13.7 | 1.4 | 1.73 | 0.51 |
| $L_3$–$L_4$ IVD | 6 | 26.0 | 6.1 | 13.7 | 1.4 | 1.91 | 0.42 |
| $L_4$ TP | 6 | 17.1 | 10.8 | 13.7 | 1.4 | 1.20 | 0.66 |
| $L_4$–$L_5$ IVD | 6 | 15.8 | 5.2 | 13.7 | 1.4 | 1.19 | 0.47 |
| $L_5$ TP | 4 | 5.4 | 4.5 | 14.0 | 1.4 | 0.36 | 0.29 |
| $L_5$ VB | 3 | 11.3 | 0.8 | 14.3 | 0.6 | 0.79 | 0.08 |

Fascicles are identified by their segmental origin and attachment to the vertebral body (VB), transverse process (TP), or intervertebral disc (IVD).

0.5 cm) regardless of their level of origin. Different specimens exhibited quite similar lengths of fascicles (14, 15, and 12 cm respectively).

Within the body of the intact psoas major the various fascicles were arranged systematically from before backwards and from above downwards. Across the belly of psoas major, the fascicles were arranged in a laminated fashion, with those from higher segmental levels covering the anterior and then medial aspects of those from successively lower levels. This endowed the muscle with the appearance of having been twisted medially (which is consistent with the rotation of the lower limb undergone during development). The laminated structure of the muscle was propagated into its tendon. The tendon of the $L_4$–$L_5$ fascicle formed the central core of the common tendon while the tendons from successively higher levels wrapped circumferentially around this core.

From above downwards the fascicles were staggered. Because each fascicle had the same length, fascicles from higher levels became tendinous while still covering fleshy fibres from lower levels, such that the fascicle from $L_5$ was the last to join the psoas tendon and was still fleshy while all others had become tendinous.

In terms of relative size, the fascicles from transverse processes were generally smaller than those from the ipsisegmental disc (Table 1). From $T_{12}$–$L_1$ to $L_4$–$L_5$ the fascicles were of comparable size, but the fascicles from the $L_5$ vertebra were conspicuously smaller.

*Biomechanics*

From its origin, each fascicle passes downwards, laterally and forwards to reach the psoas tendon. From above downwards the fascicles assume a progressively less steep orientation with respect to the long axis of the vertebral column in both the anteroposterior and lateral projection (Figures 4 and 5). The lateral deviation of each fascicle as it passes caudally is not great, amounting to between 11° and 23° (Table 2). This results in virtually all of the force of the fascicle being exerted in the sagittal plane (Table 2).

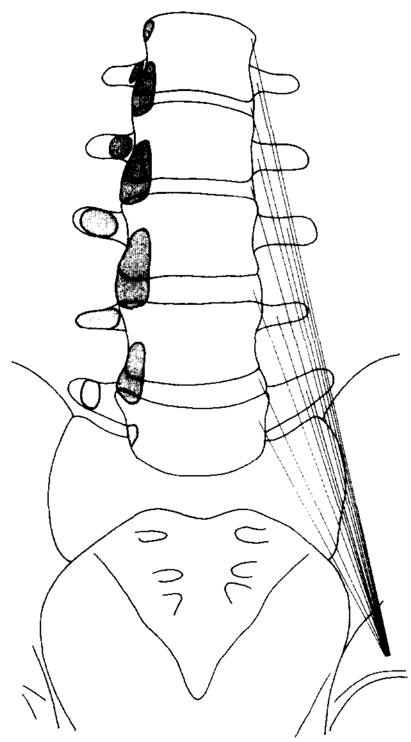

**Figure 4.** The sites of attachment (shaded areas) and the lines of action of the fascicles of psoas major as seen in anteroposterior projection.

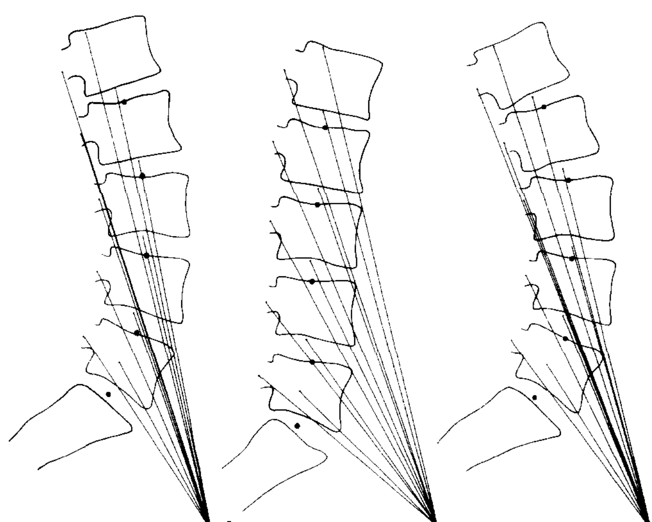


**Figure 5.** The lines of action of the fascicles of psoas major as seen in lateral projection. The points marked as the origin of each fascicle are the centroids of the areas of attachment (Figure 1). The large dots below each vertebral body mark the location of the instantaneous axis of rotation of the vertebra above. **a**, erect posture; **b**, full flexion of the lumbar spine; **c**, full extension of the lumbar spine.

**Table 2.** Morphometric and trigonometric parameters of the fascicles of psoas major in the erect posture

| Fascicle | *PI (mm)* | | *OP (mm)* | | *μ* | cos μ | $F_{max}$ | $F_{sag}$ |
|---|---|---|---|---|---|---|---|---|
| | *Mean* | SD | *Mean* | SD | *(degrees)* | | | |
| $L_1$ VB | 46 | 11 | 243 | 15 | 11 | 0.98 | 2.11 K | 2.1 K |
| $L_1$ TP | 46 | 10 | 235 | 15 | 11 | 0.98 | 0.61 K | 0.6 K |
| $L_1$–$L_2$ IVD | 45 | 10 | 218 | 16 | 12 | 0.98 | 2.11 K | 2.1 K |
| $L_2$ TP | 41 | 10 | 207 | 17 | 11 | 0.98 | 1.01 K | 1.0 K |
| $L_2$–$L_3$ IVD | 43 | 10 | 188 | 17 | 13 | 0.97 | 1.61 K | 1.6 K |
| $L_3$ TP | 38 | 9 | 173 | 16 | 12 | 0.98 | 1.73 K | 1.7 K |
| $L_3$–$L_4$ IVD | 43 | 8 | 151 | 16 | 16 | 0.96 | 1.91 K | 1.8 K |
| $L_4$ TP | 36 | 7 | 141 | 14 | 14 | 0.97 | 1.20 K | 1.2 K |
| $L_4$–$L_5$ IVD | 42 | 6 | 117 | 15 | 20 | 0.94 | 1.19 K | 1.1 K |
| $L_5$ TP | 31 | 5 | 115 | 11 | 15 | 0.97 | 0.36 K | 0.3 K |
| $L_5$ VB | 42 | 5 | 100 | 12 | 23 | 0.92 | 0.79 K | 0.7 K |

Fascicles are identified by their segmental origin and attachment to the vertebral body (VB), transverse process (TP), or intervertebral disc (IVD). PI represents the lateral displacement of the caudal end of the fascicle (in the iliopsoas tendon at the iliopubic eminence) with respect to its origin. OP is the length of the fascicle from its origin to the iliopubic eminence, as projected in the sagittal plane. The angle $\mu$ is the angle subtended by PI at the origin of the fascicle. The force $F_{max}$ is the maximum force of the fascicle and is expressed as the product of its physiological cross-sectional area and the force coefficient, K, whose value is unknown but whose dimensions are N cm$^{-2}$. The force $F_{sag}$ is the force exerted by the fascicle in the sagittal plane.

In the erect posture, the fascicles assume various relationships with the instantaneous axes of rotation of the lumbar motion segments. One example is illustrated in Figure 5a, which shows that fascicles from different levels run behind some axes but in front of others. The exact relationship between a given fascicle and a given axis varied, however, from subject to subject. As a consequence, not only the length of the moment arm but also its direction varied. The average moment arms and their directions for all ten subjects are summarized in Table 3. Overall, the moment arms are quite short, the longest occurring at the $L_5$–$S_1$ level but measuring not more than 31 mm on the average.

Coupling the data on moment arms and physiological cross-sectional area allows the relative forces exerted by the psoas on each segment in the erect posture to be calculated (Table 3). It is evident from this table that the magnitude of the maximum moments that can be exerted by each fascicle and by the fascicles collectively are quite small, but moreover, in the upright posture psoas exerts a net extension moment on the upper three lumbar segments. Only the lower two segments are flexed by psoas.

In lateral projections of the erect posture, the fascicles of psoas major from above downwards assume a progressively less steep orientation with respect to their vertebra of origin. As a result of this, the upper fascicles exert relatively more of their force in compression than in shear (Table 4). From above downwards, the total compression loads and total

**Table 3.** Mean magnitudes and SD of the moment arms (Ma) of the fascicles of psoas major for each segment that a fascicle crosses, as determined in ten subjects, and the mean maximum moments (Mo) that could be exerted by each fascicle on each lumbar motion segment in the sagittal plane in the erect posture

| *Fascicle* | *Moment arms (mm) and moments (N m × 10$^{-3}$) by segmental level* | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *$L_1$–$L_2$* | | | *$L_2$–$L_3$* | | | *$L_3$–$L_4$* | | | *$L_4$–$L_5$* | | | *$L_5$–$S_1$* | | |
| | *Ma* | SD | *Mo* | *Ma* | SD | *Mo* | *Ma* | SD | *Mo* | *Ma* | SD | *Mo* | *Ma* | SD | *Mo* |
| $L_1$ VB | −7 | 7 | −15 K | −7 | 7 | −15 K | −2 | 7 | −4 K | 11 | 10 | 23 K | 29 | 15 | 61 K |
| $L_1$ TP | −1 | 6 | −8 K | −17 | 7 | −10 K | −10 | 7 | −6 K | 6 | 10 | 4 K | 24 | 31 | 14 K |
| $L_1$–$L_2$ IVD | −1 | 3 | −2 K | −2 | 7 | −4 K | 1 | 6 | 2 K | 14 | 10 | 29 K | 31 | 14 | 65 K |
| $L_2$ TP | | | | −18 | 5 | −18 K | −12 | 6 | −12 K | 4 | 10 | 4 K | 22 | 14 | 22 K |
| $L_2$–$L_3$ IVD | | | | 1 | 4 | 2 K | 4 | 6 | 6 K | 15 | 9 | 24 K | 31 | 13 | 50 K |
| $L_3$ TP | | | | | | | −14 | 4 | −24 K | 3 | 9 | 5 K | 22 | 12 | 37 K |
| $L_3$–$L_4$ IVD | | | | | | | −2 | 4 | 4 K | 15 | 6 | 27 K | 30 | 10 | 54 K |
| $L_4$ TP | | | | | | | | | | −2 | 6 | −2 K | 17 | 10 | 20 K |
| $L_4$–$L_5$ IVD | | | | | | | | | | 6 | 3 | 7 K | 23 | 8 | 25 K |
| $L_5$ TP | | | | | | | | | | | | | 6 | 7 | 2 K |
| $L_5$ VB | | | | | | | | | | | | | 11 | 6 | 8 K |
| Sum (Nm × 10$^{-3}$) | | | −25 K | | | −45 K | | | −34 K | | | 121 K | | | 358 K |

A negative sign indicates an extension moment arm and moment; all other values are flexion moment arms and moments. Moments are expressed in units of N m × 10$^{-3}$ and as multiples of a force coefficient, K, whose value is unknown but whose dimensions would be N cm$^{-2}$. Fascicles are identified by their segmental origin and attachment to the vertebral body (VB), transverse process (TP), or intervertebral disc (IVD).

**Table 4.** Mean magnitudes and (SD) of the orientation (λ, degrees) of each fascicle of psoas major with respect to the transverse plane of each vertebra on which the fascicle acts in the erect posture and the mean maximum compression force ($F_c$) and shear force ($F_s$), measured in Newtons, exerted by each fascicle on each segment

| *Fascicle* | | *Orientation (λ), compression force ($F_c$) and shear force ($F_s$) by segmental level* | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | *$L_1$–$L_2$* | | | *$L_2$–$L_3$* | | | *$L_3$–$L_4$* | | | *$L_4$–$L_5$* | | | *$L_5$–$S_1$* | | |
| | $F_{sag}$ | λ | $F_c$ | $F_s$ | λ | $F_c$ | $F_s$ | λ | $F_c$ | $F_s$ | λ | $F_c$ | $F_s$ | λ | $F_c$ | $F_s$ |
| $L_1$ VB | 2.1 K | 90(5) | 2.1 K | 0.0 K | 87(4) | 2.1 K | 0.1 K | 79(8) | 2.1 K | 0.4 K | 67(7) | 1.9 K | 0.8 K | 51(8) | 1.6 K | 1.3 K |
| $L_1$ TP | 0.6 K | 87(5) | 0.6 K | 0.0 K | 84(4) | 0.6 K | 0.1 K | 76(8) | 0.6 K | 0.1 K | 64(7) | 0.5 K | 0.3 K | 46(9) | 0.4 K | 0.4 K |
| $L_1$–$L_2$ IVD | 2.1 K | | | | 88(4) | 2.1 K | 0.1 K | 81(7) | 2.1 K | 0.3 K | 68(7) | 1.9 K | 0.8 K | 52(8) | 1.7 K | 1.3 K |
| $L_2$ TP | 1.0 K | | | | 85(6) | 1.0 K | 0.1 K | 77(8) | 1.0 K | 0.2 K | 64(7) | 0.9 K | 0.4 K | 46(8) | 0.7 K | 0.7 K |
| $L_2$–$L_3$ IVD | 1.6 K | | | | | | | 83(8) | 1.6 K | 0.2 K | 70(7) | 1.5 K | 0.5 K | 54(8) | 1.3 K | 0.9 K |
| $L_3$ TP | 1.7 K | | | | | | | 76(8) | 1.6 K | 0.4 K | 64(8) | 1.5 K | 0.7 K | 45(9) | 1.2 K | 1.2 K |
| $L_3$–$L_4$ IVD | 1.8 K | | | | | | | | | | 70(8) | 1.7 K | 0.6 K | 52(10) | 1.4 K | 1.1 K |
| $L_4$ TP | 1.2 K | | | | | | | | | | 61(9) | 1.0 K | 0.6 K | 42(11) | 0.8 K | 0.9 K |
| $L_4$–$L_5$ IVD | 1.1 K | | | | | | | | | | | | | 46(12) | 0.8 K | 0.8 K |
| $L_5$ TP | 0.3 K | | | | | | | | | | | | | 34(13) | 0.2 K | 0.2 K |
| $L_5$ VB | 0.7 K | | | | | | | | | | | | | 37(14) | 0.4 K | 0.6 K |
| Sum (compression) | | | 2.7 K | | | 5.8 K | | | 9.0 K | | | 10.9 K | | | 10.5 K | |
| Sum (shear) | | | | 0.0 K | | | 0.4 K | | | 1.6 K | | | 4.7 K | | | 9.5 K |

Forces are expressed as multiples of a force coefficient, K, whose value is unknown but whose dimensions are N cm$^{-2}$. Fascicles are identified by their segmental origin and attachment to the vertebral body (VB), transverse process (TP), or intervertebral disc (IVD).

anterior shear loads on the lumbar motion segments increase, and the $L_5$–$S_1$ segment is subjected to almost as much shear as compression (Table 4).

Flexion of the lumbar spine has the effect of shortening the fascicles of psoas and altering their relationship with the instantaneous axes of rotation, thereby altering their moment arms (Figure 5b). Upon flexion of the lumbar spine, without hip flexion, the upper fascicles of psoas shorten by 5–14 mm while the lower fascicles exhibit little change in length (Table 5). The moment arms of fascicles increase in magnitude in a positive sense; flexion moment arms become larger and extension moment arms become smaller or convert to flexion moment arms (Table 5). The upper fascicles of psoas exert flexion moments instead of extension moments. The flexion moments exerted on lower lumbar segments are appreciably larger than in the erect posture but overall, all moments remain relatively small (Table 5).

Upon flexion the orientation of the fascicles with respect to their vertebra of origin changes both because of the sagittal rotation that each vertebra undergoes and because of the forward displacement of the vertebra as the lumbar spine flexes. Consequently, the compression force exerted by each fascicle decreases as its shear force increases (Table 6). The total

**Table 5.** Changes in length undergone by the fascicles of psoas major upon assumption of the fully flexed position of the lumbar spine, the mean magnitudes and SD of the moment arms (Ma) of the fascicles for each segment that a fascicle crosses, as determined in ten subjects, and the mean maximum moments (Mo) that could be exerted by each fascicle on each lumbar motion segment in the sagittal plane in full flexion of the lumbar spine

| *Fascicle* | *Change in length (mm)* | | *Moment arms (mm) and moments (N m × 10$^{-3}$) by segmental level* | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *Mean* | *SD* | *$L_1$–$L_2$* | | | *$L_2$–$L_3$* | | | *$L_3$–$L_4$* | | | *$L_4$–$L_5$* | | | *$L_5$–$S_1$* | | |
| | | | *Ma* | *SD* | *Mo* | *Ma* | *SD* | *Mo* | *Ma* | *SD* | *Mo* | *Ma* | *SD* | *Mo* | *Ma* | *SD* | *Mo* |
| $L_1$ VB | −14 | 9 | 9 | 6 | 19 K | 22 | 8 | 46 K | 33 | 7 | 69 K | 46 | 7 | 97 K | 57 | 10 | 120 K |
| $L_1$ TP | −8 | 7 | −5 | 5 | −3 K | 10 | 7 | 6 K | 27 | 7 | 16 K | 34 | 8 | 20 K | 52 | 10 | 31 K |
| $L_1$–$L_2$ IVD | −14 | 8 | 4 | 4 | 8 K | 17 | 7 | 36 K | 30 | 6 | 63 K | 43 | 7 | 90 K | 55 | 10 | 116 K |
| $L_2$ TP | −6 | 6 | | | | −3 | 6 | −3 K | 14 | 5 | 14 K | 31 | 7 | 31 K | 46 | 10 | 46 K |
| $L_2$–$L_3$ IVD | −13 | 6 | | | | 6 | 3 | 10 K | 20 | 4 | 32 K | 39 | 8 | 62 K | 50 | 9 | 80 K |
| $L_3$ TP | −5 | 4 | | | | | | | 0 | 4 | 0 K | 22 | 6 | 37 K | 39 | 9 | 66 K |
| $L_3$–$L_4$ IVD | −10 | 4 | | | | | | | 6 | 3 | 11 K | 26 | 4 | 47 K | 42 | 7 | 76 K |
| $L_4$ TP | −2 | 3 | | | | | | | | | | 7 | 5 | 8 K | 27 | 8 | 32 K |
| $L_4$–$L_5$ IVD | −4 | 3 | | | | | | | | | | 8 | 3 | 9 K | 28 | 6 | 31 K |
| $L_5$ TP | 0 | 2 | | | | | | | | | | | | | 9 | 6 | 3 K |
| $L_5$ VB | −1 | 2 | | | | | | | | | | | | | 12 | 6 | 8 K |
| Sum (N m × 10$^{-3}$) | | | | | 24 K | | | 95 K | | | 205 K | | | 401 K | | | 609 K |

A negative sign indicates an extension moment arm and moment; all other values are flexion moment arms and moments. Moments are expressed in units of N m × 10$^{-3}$ and as multiples of a force coefficient, K, whose value is unknown but whose dimensions would be N cm$^{-2}$. Fascicles are identified by their segmental origin and attachment to the vertebral body (VB), transverse process (TP), or intervertebral disc (IVD).

**Table 6.** Mean magnitudes and (SD) of the orientation (λ, degrees) of each fascicle of psoas major with respect to the transverse plane of each vertebra on which the fascicle acts in the fully flexed posture of the lumbar spine, and the mean maximum compression force ($F_c$) and shear force ($F_s$), measured in Newtons, exerted by each fascicle on each segment

| *Fascicle* | | *Orientation (λ), compression force ($F_c$) and shear force ($F_s$) by segmental level* | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | *$L_1$–$L_2$* | | | *$L_2$–$L_3$* | | | *$L_3$–$L_4$* | | | *$L_4$–$L_5$* | | | *$L_5$–$S_1$* | | |
| | $F_{sag}$ | λ | $F_c$ | $F_s$ | λ | $F_c$ | $F_s$ | λ | $F_c$ | $F_s$ | λ | $F_c$ | $F_s$ | λ | $F_c$ | $F_s$ |
| $L_1$ VB | 2.1 K | 64(7) | 1.9 K | 0.9 K | 67(4) | 1.9 K | 0.8 K | 70(5) | 2.0 K | 0.7 K | 69(5) | 2.0 K | 0.8 K | 62(8) | 1.9 K | 1.0 K |
| $L_1$ TP | 0.6 K | 59(7) | 0.5 K | 0.3 K | 63(4) | 0.5 K | 0.3 K | 66(5) | 0.5 K | 0.2 K | 64(5) | 0.5 K | 0.3 K | 58(8) | 0.5 K | 0.3 K |
| $L_1$–$L_2$ IVD | 2.1 K | | | | 66(4) | 1.9 K | 0.9 K | 69(5) | 2.0 K | 0.8 K | 67(4) | 1.9 K | 0.8 K | 60(8) | 1.8 K | 1.1 K |
| $L_2$ TP | 1.0 K | | | | 59(4) | 0.9 K | 0.5 K | 61(5) | 0.9 K | 0.5 K | 60(4) | 0.9 K | 0.5 K | 53(8) | 0.8 K | 0.6 K |
| $L_2$–$L_3$ IVD | 1.6 K | | | | | | | 64(6) | 1.4 K | 0.7 K | 63(5) | 1.4 K | 0.7 K | 57(7) | 1.3 K | 0.9 K |
| $L_3$ TP | 1.7 K | | | | | | | 54(6) | 1.4 K | 1.0 K | 53(6) | 1.4 K | 1.0 K | 47(9) | 1.2 K | 1.2 K |
| $L_3$–$L_4$ IVD | 1.8 K | | | | | | | | | | 55(7) | 1.5 K | 1.0 K | 49(4) | 1.4 K | 1.2 K |
| $L_4$ TP | 1.2 K | | | | | | | | | | 45(7) | 0.8 K | 0.8 K | 38(10) | 0.7 K | 0.9 K |
| $L_4$–$L_5$ IVD | 1.1 K | | | | | | | | | | | | | 38(11) | 0.7 K | 0.9 K |
| $L_5$ TP | 0.3 K | | | | | | | | | | | | | 26(12) | 0.1 K | 0.3 K |
| $L_5$ VB | 0.7 K | | | | | | | | | | | | | 28(13) | 0.3 K | 0.6 K |
| Sum (compression) | | | 2.4 K | | | 5.2 K | | | 8.2 K | | | 10.4 K | | | 10.7 K | |
| Sum (shear) | | | | 1.2 K | | | 2.5 K | | | 3.9 K | | | 5.9 K | | | 9.0 K |

Forces are expressed as multiples of a force coefficient, K, whose value is unknown but whose dimensions are N $cm^{-2}$. Fascicles are identified by their segmental origin and attachment to the vertebral body (VB), transverse process (TP), or intervertebral disc (IVD).

compression force on each segment differs little from that exerted in the erect posture. The shear force exerted on $L_5$–$S_1$ is about the same as in the erect posture but is somewhat larger at higher levels (Table 6).

Upon extension of the lumbar spine without hip movement, the fascicles of psoas lengthen slightly and their moment arms change (Figure 5c, Table 7). The upper lumbar segments are subjected to extension moments that are substantially larger than those exerted in the erect posture. The $L_4$ and $L_5$ segments remain subject to flexion moments but these are smaller than those experienced in the erect posture (Table 7).

Extension alters the orientation of the fascicles with respect to their vertebra of origin. As a result the compression force and shear force exerted by each fascicle changes. In extension the compression force of each fascicle and the total compression force on each segment are not greatly different from those exerted in the erect posture (Table 8). Shear forces at lower lumbar segments in extension are not greatly different from those in the erect posture, but at upper lumbar levels, shear forces are reversed by the posterior sagittal rotation of the upper lumbar vertebrae, and posterior shear forces are exerted (Table 8).

**Table 7.** Changes in length undergone by the fascicles of psoas major upon assumption of the fully extended position of the lumbar spine, the mean magnitudes and SD of the moment arms (Ma) of the fascicles for each segment that a fascicle crosses, as determined in ten subjects, and the mean maximum moments (Mo) that could be exerted by each fascicle on each lumbar motion segment in the sagittal plane in full extension of the lumbar spine

| *Fascicle* | *Change in length (mm)* | | *Moment arms (mm) and moments (N m × $10^{-3}$) by segmental level* | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | *$L_1$–$L_2$* | | | *$L_2$–$L_3$* | | | *$L_3$–$L_4$* | | | *$L_4$–$L_5$* | | | *$L_5$–$S_1$* | | |
| | *Mean* | *SD* | *Ma* | *SD* | *Mo* | *Ma* | *SD* | *Mo* | *Ma* | *SD* | *Mo* | *Ma* | *SD* | *Mo* | *Ma* | *SD* | *Mo* |
| $L_1$ VB | 1 | 6 | −13 | 5 | −27 K | −17 | 7 | −36 K | −13 | 7 | −27 K | 0 | 9 | 0 K | 18 | 14 | 38 K |
| $L_1$ TP | −1 | 4 | −23 | 4 | −14 K | −25 | 6 | −15 K | −19 | 6 | −11 K | −5 | 9 | −3 K | 14 | 14 | 8 K |
| $L_1$–$L_2$ IVD | 4 | 6 | −2 | 3 | −4 K | −8 | 6 | −17 K | −6 | 7 | −1 K | 6 | 9 | 1 K | 23 | 14 | 48 K |
| $L_2$ TP | 1 | 4 | | | | −22 | 5 | −22 K | −18 | 6 | −18 K | −4 | 9 | −4 K | 15 | 13 | 15 K |
| $L_2$–$L_3$ IVD | 4 | 4 | | | | 0 | 4 | 0 K | 0 | 5 | 0 K | 9 | 9 | 14 K | 25 | 13 | 40 K |
| $L_3$ TP | 2 | 3 | | | | | | | −16 | 4 | −27 K | −2 | 7 | −3 K | 16 | 11 | 27 K |
| $L_3$–$L_4$ IVD | 3 | 4 | | | | | | | 1 | 2 | 2 K | 11 | 5 | 20 K | 26 | 9 | 47 K |
| $L_4$ TP | 2 | 3 | | | | | | | | | | −4 | 5 | −5 K | 14 | 9 | 17 K |
| $L_4$–$L_5$ IVD | 3 | 3 | | | | | | | | | | 4 | 3 | 4 K | 21 | 7 | 23 K |
| $L_5$ TP | 1 | 2 | | | | | | | | | | | | | 7 | 10 | 2 K |
| $L_5$ VB | 1 | 2 | | | | | | | | | | | | | 10 | 6 | 7 K |
| Sum (N m × $10^{-3}$) | | | | | −45 K | | | −90 K | | | −82 K | | | 24 K | | | 272 K |

A negative sign indicates an extension moment arm and moment; all other values are flexion moment arms and moments. Moments are expressed in units of N m × $10^{-3}$ and as multiples of a force coefficient, K, whose value is unknown but whose dimensions would be N $cm^{-2}$. Fascicles are identified by their segmental origin and attachment to the vertebral body (VB), transverse process (TP), or intervertebral disc (IVD).

**Table 8.** Mean magnitude and (SD) of the orientation (λ, degrees) of each fascicle of psoas major with respect to the transverse plane of each vertebra on which the fascicle acts in the fully extended position of the lumbar spine, as determined in 10 subjects, and the mean maximum compression force ($F_c$) and shear force ($F_s$), measured in Newtons, exerted by each fascicle on each segment

| Fascicle | | Orientation (λ), compression force ($F_c$) and shear force ($F_s$) by segmental level | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $L_1$–$L_2$ | | | $L_2$–$L_3$ | | | $L_3$–$L_4$ | | | $L_4$–$L_5$ | | | $L_5$–$S_1$ | | |
| | $F_{sag}$ | λ | $F_c$ | $F_s$ | λ | $F_c$ | $F_s$ | λ | $F_c$ | $F_s$ | λ | $F_c$ | $F_s$ | λ | $F_c$ | $F_s$ |
| $L_1$ VB | 2.1 K | 99(3) | 2.1 K | –0.3 K | 92(4) | 2.1 K | –0.1 K | 82(7) | 2.1 K | 0.3 K | 67(6) | 1.9 K | 0.8 K | 48(7) | 1.6 K | 1.4 K |
| $L_1$ TP | 0.6 K | 97(3) | 0.6 K | –0.1 K | 90(4) | 0.6 K | 0.0 K | 79(7) | 0.6 K | 0.1 K | 64(6) | 0.5 K | 0.3 K | 46(7) | 0.4 K | 0.4 K |
| $L_1$–$L_2$ IVD | 2.1 K | | | | 95(3) | 2.1 K | –0.2 K | 84(7) | 2.1 K | 0.2 K | 70(5) | 2.0 K | 0.7 K | 51(7) | 1.6 K | 1.3 K |
| $L_2$ TP | 1.0 K | | | | 95(6) | 1.0 K | 0.0 K | 81(8) | 1.0 K | 0.2 K | 66(6) | 0.9 K | 0.4 K | 49(8) | 0.8 K | 0.7 K |
| $L_2$–$L_3$ IVD | 1.6 K | | | | | | | 87(7) | 1.6 K | 0.1 K | 73(6) | 1.5 K | 0.5 K | 54(7) | 1.3 K | 0.9 K |
| $L_3$ TP | 1.7 K | | | | | | | 81(8) | 1.7 K | 0.3 K | 67(7) | 1.6 K | 0.7 K | 47(9) | 1.2 K | 1.2 K |
| $L_3$–$L_4$ IVD | 1.8 K | | | | | | | | | | 74(7) | 1.7 K | 1.5 K | 54(9) | 1.5 K | 1.1 K |
| $L_4$ TP | 1.2 K | | | | | | | | | | 65(8) | 1.1 K | 0.5 K | 45(10) | 0.8 K | 0.8 K |
| $L_4$–$L_5$ IVD | 1.1 K | | | | | | | | | | | | | 51(11) | 0.9 K | 0.7 K |
| $L_5$ TP | 0.3 K | | | | | | | | | | | | | 39(12) | 0.2 K | 0.2 K |
| $L_5$ VB | 0.7 K | | | | | | | | | | | | | 43(13) | 0.5 K | 0.5 K |
| Sum (compression) | | | 2.7 K | | | 5.8 K | | | 9.1 K | | | 11.2 K | | | 10.8 K | |
| Sum (shear) | | | | –0.4 K | | | –0.3 K | | | 1.2 K | | | 4.4 K | | | 9.2 K |

Forces are expressed as multiples of a force coefficient, K, whose value is unknown but whose dimensions are N $cm^{-2}$. A negative sign indicates a posterior shear force; all other shear forces are directed anteriorly. Fascicles are identified by their segmental origin and attachment to the vertebral body (VB), transverse process (TP), or intervertebral disc (IVD).

## Discussion

The present study constitutes the first detailed examination of the fascicular and segmental anatomy of the psoas major. The muscle was found to consist of several fascicles with constant, discrete areas of origin. To form the intact muscle these fascicles are aggregated in a concentric, laminated fashion with fibres from high lumbar levels spiralling anteromedially around those from lower levels, with the concentric lamination being propagated into the psoas tendon.

Textbooks of anatomy emphasize the origin of psoas from tendinous arches that bridge consecutive intervertebral discs, forming a tunnel around the waist of the vertebral body that allows passage of the lumbar vessels and rami communicantes[1]. Such distinct arches were not encountered in the present study. The deepest, most medial, fleshy fibres of psoas could be readily traced to distinct sites of attachment to an intervertebral disc or to the adjacent margin of the vertebral body. At most, any apparent tendinous arch on the medial surface of psoas would constitute no more than a thickening of deep fascia at this site; it does not constitute a separate site of attachment.

A striking feature of the fascicles of psoas major was their similarity of length. Within a given specimen, the fascicles measured within a centimetre in length, and differences between specimens were not large. This morphological feature has a bearing on the purported functions of psoas major.

As the lumbar spine bends in either the sagittal or coronal plane, upper lumbar vertebrae undergo a far greater arcuate excursion than lower vertebrae. Consequently, if psoas were designed to execute or control such movements, one would expect longer fascicles attaching to segments that underwent greater arcuate excursions in order to control this movement throughout its range. The fact that the fascicles of psoas are uniform in length suggests that, to the contrary, the psoas is designed to act from the lumbar spine on the femur. With all fascicles of similar length, they would all undergo the same relative shortening and would share to the same extent the linear excursion of their common site of attachment on the femur. This inference is supported by consideration of the biomechanics of the psoas fascicles.

In all positions of the lumbar spine the lines of action of the fascicles of psoas run very close to the instantaneous axes of rotation of all lumbar motion segments. Consequently their moment arms are very small, and regardless of the size of any fascicle the moment it might exert is thus small. Furthermore, in different individuals the moment arms of upper lumbar fascicles vary from extensor to flexor in the erect posture, so there is no consistent design for these fascicles to be flexors or extensors. Upon assumption of the flexed posture of the lumbar spine, more fascicles become consistently flexor but the moments they produce are still compromised by very short moment arms. In extension upper lumbar fascicles are more consistently extensors, but inconsistencies pertain at both $L_3$–$L_4$ and $L_4$–$L_5$ (Table 7). Only the $L_5$–$S_1$ level is regularly subject to flexion moments by all fascicles in all positions of the lumbar spine, but even then the total moment is relatively small.

The actual magnitude of the force exerted by psoas is a vexatious issue because the value of the force coefficient relating maximum force to physiological cross-sectional area is unknown. For this reason, in the present study the value of the force coefficient has been treated as an unknown. Nevertheless, the results of the present study have been presented in such a way that once and if a value of the force coefficient is determined, the segmental forces can be readily computed. Meanwhile the tables of results illustrate the relative magnitude of moments, compression forces and shear forces exerted on each segment and by each component of psoas major.

For the purposes of illustration, it is arguably defensible to assume a possible value of the force coefficient from the range ascribed to the back muscles[12], *viz.* 30–90 N $cm^{-2}$. To this end, Table 9 summarizes the forces exerted by psoas major assuming a coefficient of 50 N $cm^{-2}$. This revealed that the moments exerted by psoas are relatively trivial: a maximum of 30.5 N m at $L_5$–$S_1$ in full flexion. This is barely a quarter of the moment required to flex the trunk at $L_5$ from a supine position.

On the other hand the compression forces and shear forces exerted by a single psoas muscle are considerable. Compression forces at $L_3$–$L_4$, $L_4$–$L_5$, and $L_5$–$S_1$ approach or even exceed trunk weight, while the shear forces at $L_5$–$S_1$ are approximately equal to trunk weight (Table 9). The forces are approximately the same regardless of the posture of the lumbar spine.

Legitimate reservations may be raised concerning the confidence of these quantitative derivations. Apart from a proper value of the force coefficient, force calculations are reliant on accurate, representative measures of physiological cross-sectional area. The present data are compromised in this regard. On a small number of specimens, the volumes and physiological cross-sectional areas of the various fascicles showed considerable variation (Table 1) with coefficients of variation ranging between 21 and 55% for the regularly occurring fascicles. Furthermore, the morphometric data were drawn from elderly specimens, which could have had muscles that are smaller than those of average young or middle-aged adults.

These limitations could be overcome by performing more dissections and in a greater number of younger specimens. However, it is questionable whether the putative additional gain in confidence would justify the investment necessary to overcome the logistic difficulties of studying young specimens and the time required to perform multiple, meticulous dissections. In this regard, we submit that the morphometric data presented here are not unrealistic, and reasonably represent the order of magnitude of forces involved.

In contrast, the geometric data presented are more representative. The lengths, orientations, and disposition of the fascicles of psoas were derived from radiographs of young males. The variance in measures of lengths and angles is tolerably small, and the maximum variations incurred would not alter the final calculations by any more than a factor of two. Thus, whatever arguments might be raised concerning the confidence of the actual magnitude of forces, the present study presents reliable data on the changes and distribution of these forces in different postures of the lumbar spine, whereupon instructive conclusions may be drawn about the muscle and its action on the lumbar spine.

The psoas major is not designed as a prime mover of the lumbar spine. In all postures of the lumbar spine in the sagittal plane, the moments psoas can exert are very small. In the erect posture the psoas major tends to extend the upper lumbar vertebrae and to flex the lower lumbar vertebrae. This action is accentuated in extension. In flexion all components of psoas tend to flex the entire lumbar spine, but even then the total moment exerted is alone not even enough to flex the lumbar spine in the exercise of sit-ups.

What the psoas does do is exert substantial compression loads and shear loads on the lumbar spine. In fact, its action in the erect or extended posture could be interpreted as vertically crumpling the lumbar spine in a sigmoid fashion forcing it into lordosis while severely shearing the $L_5$–$S_1$ joint. Those that prescribe sit-ups, either in sports training or in spinal rehabilitation should consider whether this is the effect they wish to achieve by their prescription. The shear force exerted on $L_5$–$S_1$ by maximum contraction of a single psoas muscle is approximately twice that exerted on this joint by trunk weight in upright standing. Whatever benefit might be gained by strengthening the psoas muscle by sit-ups has to be traded against the strain sustained by the $L_5$–$S_1$ joints and the pars interarticularis that resist this shear.

These conclusions are perforce restricted to the actions of psoas major in the sagittal plane. The

**Table 9.** Summary of the total representative maximum moments (Mo), compression force ($F_c$) and shear force ($F_s$) exerted by the psoas major on each segment of the lumbar spine in the erect, fully flexed and fully extended postures of the lumbar spine, assuming a force coefficient of 50 N $cm^{-2}$

| | *Moments, compression forces ($F_c$) and shear forces ($F_s$) by segmental level* | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $L_1$–$L_2$ | | | $L_2$–$L_3$ | | | $L_3$–$L_4$ | | | $L_4$–$L_5$ | | | $L_5$–$S_1$ | | |
| | *Mo (N m)* | $F_c$ *(N)* | $F_s$ *(N)* | *Mo (N m)* | $F_c$ *(N)* | $F_s$ *(N)* | *Mo (N m)* | $F_c$ *(N)* | $F_s$ *(N)* | *Mo (N m)* | $F_c$ *(N)* | $F_s$ *(N)* | *Mo (N m)* | $F_c$ *(N)* | $F_s$ *(N)* |
| Erect posture | −1.3 | 135 | 0 | −2.3 | 290 | 20 | −1.7 | 450 | 80 | 6.1 | 545 | 235 | 17.9 | 530 | 470 |
| Full flexion | 1.2 | 120 | 60 | 4.8 | 260 | 125 | 10.3 | 410 | 195 | 20.1 | 520 | 295 | 30.5 | 535 | 445 |
| Full extension | −2.3 | 135 | −20 | −4.5 | 290 | −15 | −4.1 | 455 | 60 | 1.2 | 560 | 220 | 13.6 | 540 | 460 |

A negative sign indicates a posterior shear force or extensor moment.

absence of reliable data on the centres of rotation for lateral flexion precluded a consideration of the actions of psoas major in the coronal plane. However, the fascicles of psoas exhibit little lateral deviation from the sagittal plane (Table 2). Consequently the compression forces exerted by psoas during lateral flexion should be similar to those exerted in flexion and extension.

One might conceive that the psoas is suited to be a lateral flexor of the lumbar spine because its fibres swing away from the vertebral column and gain appreciable moment arms, particularly at lower lumbar levels. However, at most the fibres of psoas major are displaced laterally from the vertebral column by not more than 46 mm (Table 2). Consequently any moment arms would be less than this, which is of the same order of magnitude as the moment arms for flexion in the sagittal plane, which yield relatively trivial moments (Tables 5 and 9). Thus one should not expect psoas to be any better suited to be a lateral flexor than it is a flexor of the lumbar spine.

In all, the morphology and geometry of the psoas major indicate that it is designed to act on the hip. Its attachment to the lumbar spine is only adventitious and does not imply any purposeful spinal action. Such moments that it exerts on the lumbar spine are irregular and relatively trivial in magnitude compared to the forces acting on the lumbar spine, but on the other hand severe compression loads and shear loads exerted on the lumbar spine seemed to be the price paid for a well-designed flexor of the hip.

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## References

1 Williams PL, Warwick R, Dyson M, Bannister LH (eds). *Gray's Anatomy,* 37th edn. Edinburgh, Churchill Livingstone, 1989: 635–7

2 Basmajian JV. Electromyography of iliopsoas. *Anat Rec* 1958; 132: 127–32

3 Nachemson A. Electromyographic studies on the vertebral portion of the psoas muscle. *Acta Orthop Scand* 1966; 37: 177–90

4 Nachemson A. The possible importance of the psoas muscle for stabilization of the lumbar spine. *Acta Orthop Scand* 1968; 39: 47–57

5 Gracovetsky S. An hypothesis for the role of the spine in human locomotion: a challenge to current thinking. *J Biomed Eng* 1985; 7: 205–16

6 Gracovetsky S, Farfan HF, Lamy C. The mechanism of the lumbar spine. *Spine* 1981; 3: 249–62

7 Pearcy M, Portek I, Shepherd J. Three-dimensional X-ray analysis of normal movement in the lumbar spine. *Spine* 1984; 9: 294–7

8 Pearcy MJ, Bogduk N. Instantaneous axes of rotation of the lumbar intervertebral joints. *Spine* 1988; 13: 1033–41

9 Haxton HA. Absolute muscle force in the ankle flexors of man. *J Physiol* 1944; 103: 267–73

10 Morris CB. The measurement of the strength of muscle relative to the cross-section. *Res Q* 1949; 20: 295–303

11 Ikai M, Fukunaga T. Calculation of muscle strength per unit cross-sectional area by means of ultrasonic measurement. *Int Z Angew Physiol* 1968; 26: 26–32

12 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 L4/5 joint. *J Biomech* 1988; 21: 329–41