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The role of Quadratus Lumborum asymmetry in the occurrence of lesions in the lumbar vertebrae of cricket fast bowlers

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Abstract

In cricket fast bowlers an increased incidence of stress fractures or lesions in the L4 pars interarticularis is observed, which shows a strong statistical correlation with the presence of hypertrophy in the contralateral Quadratus Lumborum (QL) muscle. This study aims to find a physical explanation for this correlation.

A mathematical model was used to estimate the forces and moments on the L3 and L4 vertebrae in six postures attained during fast bowling. These forces and moments were used in finite element models to estimate the stresses in the pars interarticularis. Two scenarios were examined per posture: symmetric QL muscles, and right QL muscle volume 30% enlarged. Influence of muscle activation was also investigated.

QL asymmetry only correlates with significant stress increases when stress levels are relatively low. When stress levels are high, due to extreme posture or muscle activation, asymmetry only causes small stress changes, suggesting that asymmetry is not the cause of stress fractures in the pars. There are even indications that asymmetry might help to reduce stresses, but more detailed knowledge of the size and activation of the lumbar muscles is needed to confirm this.

Keywords:
Cricket fast bowlers, pars interarticularis, quadratus lumborum asymmetry, fractures, lumbar spine, finite element modelling, musculoskeletal modelling

1. Introduction

Low back injuries are common amongst cricket fast bowlers[1], in particular lumbar disc degeneration[2,3] and stress fractures or lesions of the lumbar vertebrae. Stress fractures often occur in the pars interarticularis as it is usually the narrowest region of the neural arch. In the general population pars interarticularis fractures have an occurrence rate of about 5%[4,5], most commonly in the lowest lumbar vertebra, L5[4]. However, amongst elite fast bowlers occurrence rates of 10 to 50% are commonly reported in the literature[6]. Bartlett et al.[6] and Elliott[7] have given extensive overviews of the relevant literature on bilateral fractures in the partes interarticulares of fast bowlers, particularly at L5, and on unilateral fractures at many levels including L4. Unilateral fractures are predominantly found on the non-dominant side to the bowling arm[3,7,8] and often over multiple levels[3]. However, fractures at multiple levels may not always have a common cause, as Engstrom[9] showed that pre-existing L5 defects are not related to pars lesions at L4. Key factors that increase the risk of back injuries have also been reported, for example by Elliott[7] and by Portus et al.[10,11], but the exact mechanics behind the relationship between these factors and the occurrence of lesions are not always known[3,7]. The main factors identified by Elliott[7] were: (a) large shoulder counter-rotation, trunk twisting and lumbar movement, which are all key features of the mixed technique of a front-on back foot placement and a side-on shoulder alignment[12]; (b) high ball release because of a straight leg at front foot impact which results in higher ground reaction forces; (c) incorrect rehabilitation; (d) overuse such as long bowling spells and a large number of games in a season; (e) physical capacities such as poor hamstring flexibility; and (f) muscle asymmetry. In particular, Engstrom et al.[13] have linked asymmetry of the Quadratus Lumborum (QL) muscle to stress fractures of the pars interarticularis.

It is this relationship between QL asymmetry and pars fractures which our study focuses upon. In the study by Engstrom et al.[13], an increased incidence was reported of unilateral lesions in the pars interarticularis of the L4 vertebra of young elite fast bowlers. Fractures occurred exclusively on the non-dominant side to the bowling hand and in the bowlers with fractures the QL on the side of the bowling hand was up to 30% larger. This large asymmetry in muscle volume was not noticed in bowlers without fractures. As yet there is no physical explanation for this strong association. The relationship between QL asymmetry and pars fractures could be explained by any of the following three hypotheses:

1. The bowling technique of these cricketers is causing unilateral hypertrophy (one-sided increased muscle growth) of the QL, which in turn causes an increase in the stress levels in the pars, eventually leading to fractures.
2. The bowling technique of these cricketers is causing both QL hypertrophy and increased stresses in the pars that lead to fractures, but the two effects are not physically related.
3. The bowling technique of these cricketers is causing increased stresses in the pars and the body develops a QL hypertrophy as a reaction to the high stresses in the pars, in an attempt to change the ‘force flow’ through the pars and reduce the stress levels.

No other mention of the association between QL asymmetry and pars fractures could be found in the literature. As mentioned, lumbar pars interarticularis fractures are common amongst fast bowlers, at many vertebral levels, both unilateral and bilateral, and there are many factors involved in the occurrence of these fractures. However, the aim of this study is specifically to examine the potential biomechanical influence of QL asymmetry in the occurrence of unilateral pars interarticularis fractures in the L4 vertebra of fast bowlers. Although finite element modelling has been used before to study pars interarticularis fractures, to our knowledge this is the first study to use finite element modelling to study the influence of muscle action on the stresses in the pars.

2. Method

A musculoskeletal Finite Element Model (FEM) was developed to assess the potential of the QL to influence the stresses in the pars, for a range of relevant body postures that have been described in the literature. A previously developed mathematical model[14], based on the lumbar spine of the Visible Man[15], was used to predict the direction and magnitude of the muscle forces and moments acting on the L4 vertebra of the bowlers. For each posture two scenarios were compared: in the first one the Physiological Cross Sectional Area (PCSA) of the left and right QL were equal, in the second one the PCSA of the right QL was increased by 30%. The results were imported into a FEM of an L4 vertebra, which estimated the stresses occurring in the pars for both scenarios.

2.1. Postural Analysis

When looking at L4 from the posterior view (Figure 1), it appears that any fractures in the left pars (for a right-handed bowler) are most likely to occur when the zygapophysial joints (z-joints) on the left side are impacted. This happens when the spine is twisted to the right, extended or bent to the left. Burnett et al.[12] described the postures a fast bowler goes through from back foot impact (BFI) to ball release (REL). We decided to focus on the postures around the moment of front foot impact (FFI) and the postures between FFI and REL. FFI occurs between 74% and 80% of the time from BFI (0%) to REL (100%). Table 1 describes all postures investigated. It shows that at the moment of ball release the most 'extreme' posture occurs. The moment of FFI is interesting because although the rotations in the lumbar spinal joints are not as large as they are at ball release, it is known[16] that large ground reaction forces occur at FFI, which could cause peak forces on the spine. It is believed that repetitive occurrence of such forces can lead to fatigue failure in the pars[17-19], but whether QL hypertrophy is a causative agent for this process is unknown.

2.2. Mathematical Model

The mathematical model of the (major) muscles acting over the lumbar spine consists of 170 fascicles representing a total of 11 muscle pairs[14]. Each muscle's PCSA is used as a measure for the maximum muscle force. Muscle attachment points have been obtained from the Visible Human. The model predicts the forces and moments occurring on the intervertebral joints in any given posture (Figure 2) using the formula: Muscle Force = K x PCSA x Activation Level, where K is the maximum muscle intensity (force per unit area), obtained from literature[20].

The muscle activation levels reported in literature[14,20-23] were usually obtained by EMG measurements on volunteers doing maximum voluntary muscle exertions while being constrained in upright stance. These may not reflect the real muscle activation levels when the same exertion is performed unrestrained or in a different posture, and are likely to be far off the activation levels occurring in fast bowling. To account for these large uncertainties in the muscle activation patterns two distinctively different sets of activation levels were investigated. The first set was the muscle activation for Right Axial Twisting (RAT) as reported in literature[14]. The second set was a presumed worst case scenario where the right QL is the only muscle activated (QL-only) with all other muscles only providing passive force due to strain. The rationale behind this set was that if the QL is indeed the cause of the L4 stress fractures, activating it by itself without any counteraction from other muscles would most likely lead to distinctive stress peaks. Conversely, if even the QL activated by itself without any counteraction from other muscles could not cause any remarkable changes in the occurring stresses, this would be a strong indicator that the QL is not causing the stress fractures.

PCSAs are not commonly reported in literature: usually cross-sectional areas (CSAs) are given without information on image orientation, muscle orientation and muscle length, making accurate PCSA calculation impossible, as reported by Gatton et al.[24]. Furthermore, most studies[20-22,25] presenting PCSAs were performed on cadaveric material and would therefore be likely to result in a considerable underestimation of the PCSAs of young top athletes. The PCSAs used in this study were derived by Gatton[14]. To evaluate the effect of PCSA underestimation four different values for the QL PCSAs were used in the model: 1. the original value being 441 mm^2 for the 5 fascicles representing the QL[23]; 2. double that value; 3. triple that value; and 4. an alternative where the fascicle of QL attaching to L4 has been made 4 times larger and the QL fascicle attaching to L3 2 times larger. These latter values were chosen to investigate the effect of underestimation of the fascicles that are expected to matter most in our study, namely those attaching to L3 and L4.

2.3. Finite Element Model

A FEM of the L4 vertebra, ligaments and intervertebral discs (IVDs) was created based upon the geometrical model of Theo Smit[26-28], obtainable from the Internet through the BEL Repository managed by the Istituti Ortopedici Rizzoli, Bologna, Italy[29]. Shell elements of 1 mm thickness were added to represent the cortical shell around the posterior elements and vertebral body. Material properties (Table 2) were based on values used in previous finite element studies of the spine[30-32], unless otherwise indicated. The gaps between the superior articular facets of L5 and the inferior facets of L4 were modelled as a low stiffness material (material properties of cancellous bone) to avoid having to model contact, which complicates FE calculations considerably. The model was fully constrained at L5, meaning that the L5 sides of the “gap material” were fully constrained, as was the inferior surface of the L4-L5 IVD. The muscle forces and attachment locations on the posterior elements, as well as the forces and moments acting upon the superior endplate and superior articular facet were derived from the mathematical model. The mathematical model was fitted to the FEM by scaling it in 3 dimensions such that a best fit was obtained for 6 landmarks (the tips of the transverse and spinous processes and three points on the superior endplate). Figure 3 shows this FEM. A second, more detailed FEM was made, comprising L3 and L4, three IVDs and associated ligaments (Figure 4). This model was also based on the same L4 model of Smit with L3 being an exact copy of L4. Again, the gaps between the articular facets were modelled as a low stiffness material to avoid having to model contact. Contrary to the L4 FEM, the L3+L4 FEM was fully constrained at the superior surface of the superior endplate of L3 and at the superior facets of L3 to maintain the chosen posture. Consequently, no forces from higher levels (L2 and up) were present. Inferiorly, the model was fully constrained at the inferior surface of the L4-L5 IVD, and constrained in the x and y directions on the L5 sides of the “gap material” between the superior articular facets of L5 and the inferior facets of L4. L5 itself was not modelled, as it was assumed not to be relevant to this study, based upon a study by Engstrom[9] showing that pre-existing L5 defects are not related to pars lesions at L4.

The mesh of the models was identical to the geometrical model, resulting in element dimensions usually in the 1-4 mm range. The models were meshed and solved in ANSYS 8.0 (University Research license; ANSYS Inc., Canonsburg, PA, USA) using a sparse matrix direct solver as chosen by the program, with default convergence criteria. A nonlinear, large-displacement static analysis type was chosen, so no inertial effects were present, and the minimum time step was set to 1e-5.

To account for uncertainty in the material properties, a sensitivity analysis was performed using the FEM of L4 only. Several parameters, one at a time, were varied to assess their influence on the results. The parameters and their alternative values were the following:

- Modulus of elasticity of cortical bone: Original value (lowest value mentioned in literature: 5 GPa); average value mentioned in literature (16.5 GPa) & highest value mentioned in literature (28 GPa)[33].
- Poisson’s ratio of cortical bone: Original value (common value mentioned in literature: 0.2) & lowest value mentioned in literature (0.1)[34].

3. Results

The L4 FEM for the “74%” posture (the posture just before FFI; posture 1 in Table 2) showed the stresses in the pars opposite to the bowling side to be much larger (up to 10x) than on the bowling-hand side when the appropriate muscles are activated for RAT. The mathematical model showed that QL produces little axial twisting moment due to the geometrical proximity of its line of action to the centre of rotation and to the impacted z-joints. Instead, the action of the QL is primarily to create a lateral bending moment.

The change in the average Von Mises stress at the location with the largest Von Mises stress in the cortical bone of the pars region (as defined in Figure 3) as well as the change in the average Von Mises stress across all the points in the (cortical) pars were examined using a FEM comparison between symmetric and asymmetric QL models in the “74%” posture. For RAT activation, the L4 FEM did not show a significant increase in Von Mises stresses in the pars due to the asymmetry in QL. In fact, the pars stresses slightly decreased due to the asymmetry. For QL-only activation, a slightly different picture appears. In this case a 30% larger right QL did increase the peak Von Mises stress by 19%. These results are summarised in Table 3. Analysis of the shear stresses for both cases showed the same behaviour, with values of about 3 times lower than the Von Mises stresses. The maximum principal stresses behaved similar as well, with values usually around 0.8 to 1.1 times the Von Mises stress.

The sensitivity to model design was investigated by comparing the results of the L4 FEM (the original model as shown in Figure 3) to those of the L3+L4 FEM shown in Figure 4. Using the L3+L4 FEM, for RAT activation the stresses for both symmetric and asymmetric QL muscles were considerably lower compared to the L4 FEM, and for both RAT and QL-only muscle activation a small stress increase due to asymmetry was noticed (see Table 3).

For RAT activation, when increasing the PCSAs of the L3 and L4 fascicles (2x and 4x respectively) of the left and right QL, asymmetry still resulted in a decrease of the stresses, but not as much as before. When increasing the PCSA of the entire QL (QLx2 and QLx3), the decrease in stresses due to asymmetry became larger. For QL-only activation, increasing the PCSA of the L3 and L4 fascicles (on both sides) caused higher stress for both “symmetric” and “asymmetric”, but the increase due to asymmetry was not as large as before. When increasing the PCSA of the entire QL (QLx2 and QLx3) the stresses for both “symmetric” and “asymmetric” increase, and the stress increase due to asymmetry became stronger. Table 4 summarises the influence of PCSA variations on the Von Mises stresses.

The other postures from Burnett et al.[12] were also investigated in combination with QL-only activation. For these muscle activation levels a 30% larger QL increased the peak Von Mises stress for all postures. It is noticed that the increase varies considerably depending on the posture, with the more extreme postures -which have much higher stresses to start with- showing smaller increases, both absolute and relative, than the postures around the moment of FFI when the rotations in the lumbar spinal joints are not as large (see Table 5).

An analysis of the sensitivity to variations in the material properties showed that although the absolute values of the stresses changed considerably when changing the Modulus of Elasticity, the relative differences between the symmetric and asymmetric scenarios were virtually unchanged by these variations (see Table 6). The Poisson’s ratio of the cortical bone was also varied, but halving its value had no appreciable influence on the Von Mises stresses.

4. Discussion

Some of the stresses observed are in the same range or higher than failure levels mentioned in literature[33], which means the FEM is probably overestimating the stresses. It is believed that this is mainly caused by the coarseness of the mesh of the model, as the peak stresses occur at points where the elements are at angles close to 90°. Exaggerated stresses at sharp edges are a common phenomenon in finite element modelling, which can only be reduced by refining the mesh in these regions. But as the mesh of our FEM was already as fine as the solid model of Smit[26-28] it was based upon, no information required for such a refinement was available. The way the IVD in the L4 FEM and the facet gaps in both FEMs were modelled might also affect the results, as some experimental changes to the material properties of the IVD and the gap showed significant changes in the stress levels observed. However, the relative differences between the symmetric and the asymmetric scenarios were hardly affected by these parameter variations, just as in the sensitivity analysis shown in Table 6. As all conclusions were based on these relative differences, it is expected that these conclusions would not be greatly affected by further mesh refinement or more accurate disc and gap modelling. Nevertheless, it should be emphasised that this numerical study is a *comparative* study at the base theoretical level as described by Viceconti et al.[35] and should be interpreted as such.

Comparing the L4 FEM to the L3+L4 FEM it is noticed that the stresses in the more complex model are considerably lower for RAT activation. This is probably due to the fact that in this model there are no forces and moments from higher levels (L2 and up) working on the vertebrae, as the model is fully constrained at the top of L3 to maintain the chosen posture. Consequently, the stress levels are much more determined by posture, and less by muscle forces, than in the L4 FEM. The complex model shows much smaller differences between the symmetric and asymmetric scenarios than the L4 model, which suggests that the boundary conditions of the L4 FEM create a worst case scenario for the stresses caused by muscle forces.

Comparing the results for the different muscle activation levels, shown in Table 3, indicates that the activation levels play a key role in determining the influence of QL asymmetry on stress levels in the pars. It could be argued that as there is a large uncertainty in the muscle activation levels, the results of this study have only a limited validity. Therefore, to account for this uncertainty, a worst case scenario for the muscle activation levels was introduced. Using this presumed worst case scenario, i.e. when only the right QL is active, the FEM does show an increase in stresses due to QL asymmetry, but only for postures where the lumbar spine hardly deviates from the normal curve it has in upright stance (Table 5). For these postures the stresses observed are much lower than for the extreme posture adopted at the moment of ball release. In this extreme posture, the stress increase is only a few percent, as the passive forces from other muscles become more influential than the forces from QL. The stresses (around 40 MPa), and their relatively large increase (approx. 7 MPa), at the moment of FFI appear irrelevant considering much larger stresses (around 140 MPa) are predicted at the moment of ball release, unless something else, such as the ground reaction force at FFI, is adding a significant amount of stress. Even then, to be more relevant the FFI stress levels would have to exceed those occurring at ball release, and at those stress levels the 7 MPa stress increase due to QL asymmetry becomes of much less relative influence. This suggests that there is little support for the first hypothesis, that QL asymmetry causes significantly increased stresses in the pars.

Using the muscle activation levels for RAT in the “74%” posture (the posture just before FFI), the L4 FEM shows a slight decrease rather than increase in stresses due to QL asymmetry, which is emphasised when the QL PCSA is increased (Table 4). This suggests that the asymmetry between left and right QL is not the cause of the fractures and may even function to reduce stresses in the pars interarticularis. This would mean that the asymmetry is not a cause but a reaction to the development of high stresses in the pars that lead to fractures. However, the validity of this conclusion depends strongly on the accuracy of the muscle activation levels and the PCSAs used.

When comparing all scenarios investigated, it becomes clear that when other muscles start to produce more force, either passively due to extreme posture or actively e.g. when using RAT activation, the overall stresses and thus the risk of pars fractures increase, while the influence of QL decreases and the influence of QL asymmetry changes from initial stress increase to stress reduction. This supports the third hypothesis: QL asymmetry is a reaction to high stresses in the pars and serves to reduce these stresses. Previous long term observations of the development of L4 fractures show that QL asymmetry develops prior to the occurrence of fractures and that a larger asymmetry corresponds with a larger chance of fractures[13]. This makes QL asymmetry a good indicator of a high stress causing technique and, as it is clearly recognisable on Magnetic Resonance Imaging, a valuable tool in identifying individuals at increased risk of this type of injury. These long term observations led to the first hypothesis, that asymmetric QL causes the fractures. However, the results from this study suggest that something else is causing high stresses and it is the repetitive occurrence of these high stresses for a long period of time that eventually leads to fatigue failure in the L4 pars. In this case, it is fair to assume that the unilateral hypertrophy starts to develop as soon as the young cricketer starts bowling frequently, and is therefore likely to become apparent well before the number of repetitions is high enough to cause fatigue failure. This would also explain the relationship between large asymmetry and higher chance of fractures: the longer the cricketer has been bowling with a technique that produces high stresses in the pars, the higher the number of repetitions will be, and therefore a) the closer the bowler will be to the 'failure number' and thus the higher the chance of fractures, and b) the further the asymmetry will have developed. The QL asymmetry obviously does not prevent L4 pars fractures, it just has the potential to postpone them by lowering the stress in the pars, which means that it will take more repetitions before fractures occur. However, the reasoning given here to support the third hypothesis can be used just as well to support the second hypothesis, that there is no direct relationship between QL asymmetry and L4 pars fractures other than a common cause. Table 4 in particular shows that it is hard to favour one hypothesis over the other without having more accurate and detailed knowledge of the size and activation of the lumbar muscles.

5. Conclusion

The data presented in this study shows that QL asymmetry may have the potential to reduce the stresses in the pars. Whether it actually does reduce these stresses, or whether QL asymmetry and L4 pars fractures are not related apart from a common cause, cannot be determined with certainty until more specific knowledge of the size and activation of the lumbar spine muscles of fast bowlers becomes available. Future work should be aimed at obtaining this detailed data and at identifying and verifying potential causes of high stresses in the L4 pars before any advice on bowling technique alterations can be derived from this study. Finally, this combination of muscle model and FEM has the potential to be a valuable technique to study the influence of posture and musculature on lumbar spine biomechanics.

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Conflict of Interest Statement

All authors declare that they have no financial and/or peronsal relationships with other people or organisations that could inappropriately influence the work presented in this paper.

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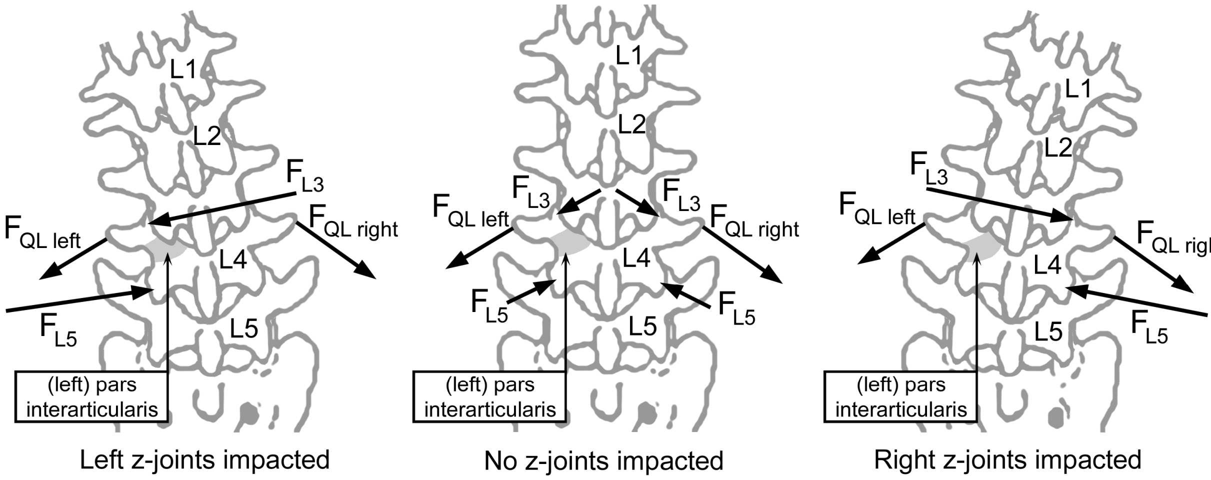

Fig. 1. Possible forces on the L4 posterior elements. The pictures show the forces exerted on L4 by the left and right QL and by L3 and L5 via the z-joints, in case the left z-joints are impacted (left picture), no z-joints are impacted (middle picture), or the right z-joints are impacted (right picture). Not shown are the forces exerted by other muscles and the forces and moments transmitted through the IVD.

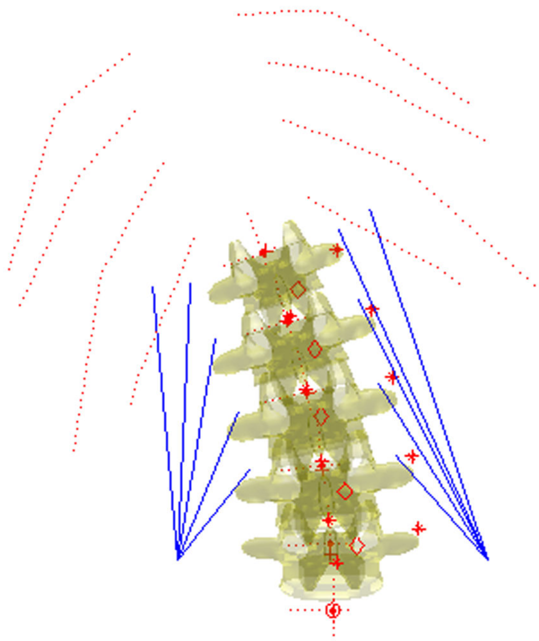

Fig. 2. Mathematical model. The figure shows the mathematical model of the lumbar spine muscles in a flexed and laterally bent posture. The dark lines represent the fascicles of the QL, the dotted lines the bottom four ribs. The symbols •, * and o indicate the exact locations of several bony landmarks, whereas the vertebrae drawn are just approximations, given only to facilitate visualisation.

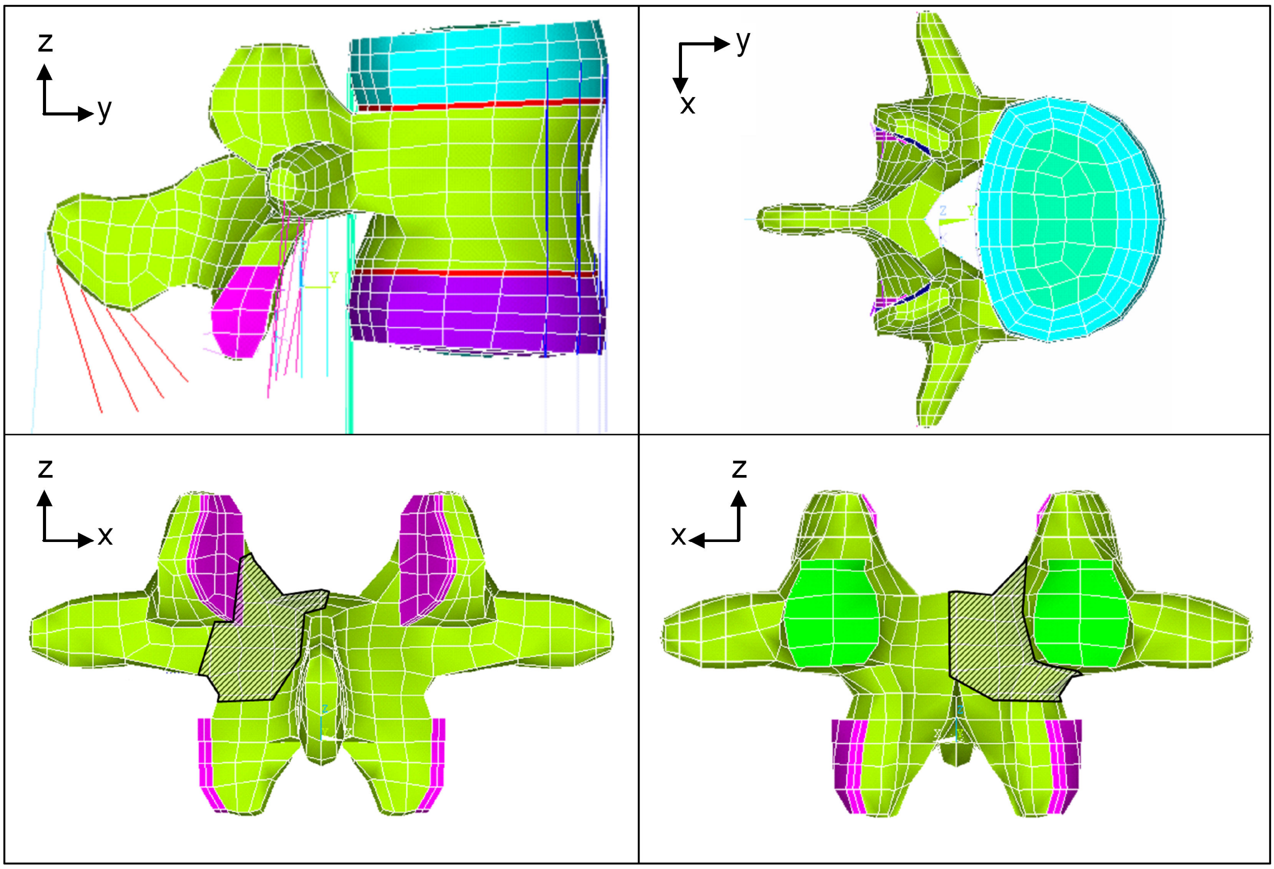

Fig. 3. L4 Finite Element Model. Top two pictures: side and top view of the finite element model of the vertebra and IVDs. Bottom two pictures: posterior and anterior view of the posterior elements, with the vertebral body, ligaments and IVDs hidden. The shaded regions indicate the pars interarticularis area.

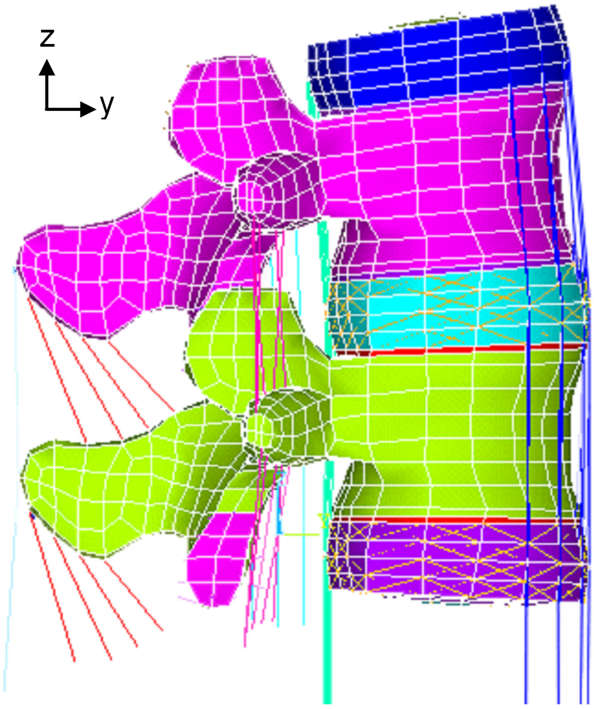

Fig. 4. Finite Element Model of L3 and L4.

Table 1
Postures. The postures are described in degrees of flexion or extension (flexion +ve), lateral bend (left +ve) and axial twist (left +ve) over the entire lumbar spine compared to upright stance.
The postures from Burnett et al. (1998) are defined on a normalised time scale with 0% being the moment of back foot impact and 100% the moment of ball release (REL), with front foot impact occurring somewhere between 74% and 80%.

	Postures from Burnett et al.(1998)					
Direction	74%	80%	86%	92%	96%	REL
Flex/Ext.	0	-2	9	26	45	55
Lat. bend	0	5	8	20	27	28
Ax. twist	-8	-6	-2	1	-6	-11

Table 1
Postures. The postures are described in degrees of flexion or extension (flexion +ve), lateral bend (left +ve) and axial twist (left +ve) over the entire lumbar spine compared to upright stance.
The postures from Burnett et al. (1998) are defined on a normalised time scale with 0% being the moment of back foot impact and 100% the moment of ball release (REL), with front foot impact occurring somewhere between 74% and 80%.

Table 2
Material properties used in the FEMs.

	Modulus of elasticity (MPa)		Poisson's ratio		Element type	Number of elements per vertebra/disc	Cross-sectional area per vertebra level (mm^2)
	L4	L3+L4	L4	L3+L4			
Nucleus pulposus	50*	1	0.1*	0.499	20 node solid	104	
Anulus ground substance	50*	4	0.1*	0.45	20 node solid	240	
Anulus fibres	*	450	*	0.3	2 node link	640	160
Endplate	24**		0.4		20 node solid	86	
Cancellous bone	74		0.2		20 node solid	1162	
Cortical bone	5000		0.2		8 node shell	744	
Anterior longitudinal ligament	11.9		0.39		2 node link	21	75.9
Posterior longitudinal ligament	12.5		0.39		2 node link	9	51.8
Ligamentum Flavum	2.4		0.39		2 node link	5	78.7
Capsular ligament	7.7		0.39		2 node link	24	102.5
Interspinous ligament	3.4		0.39		2 node link	6	36.3
Supraspinous ligament	3.4		0.39		2 node link	1	75.7
Intertransverse ligament	3.4		0.39		2 node link	10	2

* In the L4 FEM the entire IVD was modelled as a homogeneous 20 node solid material to facilitate model convergence. This material was chosen such that the deformations were similar or slightly smaller than those observed when using the heterogeneous disc, as used in the L3+L4 FEM.
** The single row of elements on the outer edge of the endplates was given a higher Modulus of elasticity (500MPa) to avoid convergence problems at the interface between the soft IVD and the stiff cortical shell.

Table 2
Material properties used in the FEMs.

Table 3
Influence of muscle activation levels and model design on the maximum and the average Von Mises stress in the pars interarticularis region (as defined in Figure 3).

Posture = "74%"	RAT		QL-only	
	L4	L3+L4	L4	L3+L4
Max VM Sym (MPa)	166	59.4	40.1	45.7
Max VM Asym (MPa)	155	59.9	47.6	46.2
Change (%)	-6.7	+0.78	+19	+1.1
Avg VM change (%)	-3.4	+0.45	+12	+0.45

VM = Von Mises stress; Sym = Symmetric QL muscles; Asym = Asymmetric QL muscles; RAT = Right Axial Twisting; QL-only = Only the right QL active; L4 = FEM shown in Fig. 3; L3+L4 = FEM shown in Fig. 4.

Table 3
Influence of muscle activation levels and model design on the maximum and the average Von Mises stress in the pars interarticularis region (as defined in Figure 3).

Table 4
Influence of muscle size (PCSA) on the maximum and the average Von Mises stress in the pars interarticularis region, using the L4 FEM in the "74%" posture.

	QLx1	QLx2	QLx3	L3x2, L4x4
Muscle activation = RAT				
Max VM Sym (MPa)	166	147	127	169
Max VM Asym (MPa)	155	124	93	166
Change (%)	-6.7	-15	-27	-1.8
Avg VM change (%)	-3.4	-7.4	-11	-0.90
Muscle activation = QL-only				
Max VM Sym (MPa)	40.1	65.1	90.3	54.4
Max VM Asym (MPa)	47.6	80.4	113	60.7
Change (%)	+19	+24	+26	+12
Avg VM change (%)	+12	+22	+26	+8.9

VM = Von Mises stress; Sym = Symmetric QL muscles; Asym = Asymmetric QL muscles; RAT = Right Axial Twisting; QL-only = Only the right QL active; QLx2 = PCSAs of the left and right QL doubled; QLx3 = PCSAs of the left and right QL tripled; L3x2,L4x4 = PCSAs of the left and right QL fascicles attaching to L3 doubled and the left and right QL fascicles attaching to L4 enlarged 4 times.

Table 4
Influence of muscle size (PCSA) on the maximum and the average Von Mises stress in the pars interarticularis region, using the L4 FEM in the "74%" posture.

Table 5
Influence of posture on the maximum and the average Von Mises stress in the pars interarticularis region, for the 6 postures defined in Table 1, using the L4 FEM. Only the right QL has been activated (QL-only).

Muscle act.=	Postures from Burnett et al. (1998)					
QL-only	74%	80%	86%	92%	96%	REL
Max VM Sym (MPa)	40.1	38.6	29.3	30.2	77.6	141
Max VM Asym (MPa)	47.6	46.4	36.2	36.1	83.8	148
Change (%)	+19	+20	+24	+20	+8.0	+4.8
Avg VM change (%)	+12	+11	+17	+12	+5.3	+3.8

VM = Von Mises stress; Sym = Symmetric QL muscles; Asym = Asymmetric QL muscles; REL= Ball release.

Table 5
Influence of posture on the maximum and the average Von Mises stress in the pars interarticularis region, for the 6 postures defined in Table 1, using the L4 FEM. Only the right QL has been activated (QL-only).

Table 6

Influence of material properties on the maximum and the average Von Mises stress in the pars interarticularis region, using the L4 FEM in the "74%" posture. The left column shows the standard situation: Modulus of elasticity = 5 GPa, Poisson's ratio = 0.2. In each of the other columns, one material property at a time is varied.

	ME=5 PR=0.2	ME = 16.5	ME = 28	PR = 0.1
Muscle activation = RAT				
Max VM Sym (MPa)	166	267	313	165
Max VM Asym (MPa)	155	249	292	154
Change (%)	-6.7	-6.6	-6.6	-6.8
Avg VM change (%)	-3.4	-3.3	-3.1	-3.4
Muscle activation = QL-only				
Max VM Sym (MPa)	40.1	60.5	70.1	42.0
Max VM Asym (MPa)	47.6	71.4	82.7	49.8
Change (%)	+19	+18	+18	+19
Avg VM change (%)	+12	+12	+12	+12

VM = Von Mises stress; Sym = Symmetric QL muscles; Asym = Asymmetric QL muscles; RAT = Right Axial Twisting; QL-only = Only the right QL active; ME = Modulus of elasticity; PR = Poisson's ratio.

Table 6

Influence of material properties on the maximum and the average Von Mises stress in the pars interarticularis region, using the L4 FEM in the "74%" posture. The left column shows the standard situation: Modulus of elasticity = 5 GPa, Poisson's ratio = 0.2. In each of the other columns, one material property at a time is varied.