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Quantitative Morphology of the Lumbar Facets, Muscles and Fascia in Relation to Core Stability

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Abstract

The morphology and function of the lumbar region is poorly understood. Better understanding of lumbar regional anatomy may enable improved understanding of lumbar stability and may also improve the clinical management of low back pain. Extensive researches have been carried out on the thoracolumbar anatomy and biomechanics. However, these studies lacked detailed anatomical knowledge about the morphology and function of the lumbar region. This study aims to provide a precise and detailed description of the anatomy of the lumbar spine and its supporting structures.

A detailed and thorough literature review of background data was undertaken. Gross degenerative features in the lumbar vertebrae were documented. Three dimensional models of the superior and inferior lumbar articular facets were created by Microscribe. This allowed calculation of the facet orientation and surface area by Rhinoceros software. The surface area was increased towards the inferior vertebral levels, while the orientation became less sagittal inferiorly. The investigations suggest that the coronally oriented facet protects and supports the facet joint, while the sagittal orientation may predispose the facet joint to degenerative spondylisthesis.

Gross observation of the thoracolumbar fascia documented the superficial myofascial thickenings, decussation and connections. The posterior and middle layers of the thoracolumbar fascia were identified. A three dimensional model enabled visualization of the bilaminar layers of the fascia which was reconstructed in a virtual space.

The morphological measurements of the lumbar multifidus, longissimus and iliocostalis muscles were taken. The cross sectional area of the multifidus muscle was increased gradually towards the L5 level. The foot prints of the multifidus, longissimus, iliocostalis lumborum and inter-spinalis muscles enabled the measurement of the surface areas of the attachments of these muscles.

The histological study revealed the fibrous enthesis of the iliocostalis muscle and its indirect attachment to the transverse process of the lumbar spine. The multifidus muscle is attached by a fibrocartilaginous enthesis to the articular process and the facet joint capsule. This study suggests that multifidus muscle supports and

stabilizes the facet joints. The lumbar enthesis investigation should receive more attention in future studies.

The clinical implications of different lumbar structures and functions may provide insight about the lumbar dysfunction. The ability to identify such differences in situ may facilitate varied clinical management of the various types of lumbar disorders.

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Publications resulting from this thesis

Sami BA, and Fogg QA (2012) Superficial muscular and fascial interactions that support the lumbar vertebral column. *Clinical Anatomy* **25 (2)**: 277 (Abstract). Abstract was presented at the Joint Summer Meeting of the European Association of Clinical Anatomy and the British Association of Clinical Anatomists, 30th June to 1st July 2011, University of Padova, Italy.

Sami BA, and Fogg QA (2013) The paravertebral lumbar muscle attachments in relation to vertebral column stability. *Clinical Anatomy* **26 (3)**: 413 (Abstract). Abstract was presented at the Summer Meeting of the British Association of Clinical Anatomists on 19th July 2012, University of Swansea, Wales.

Sami BA, and Fogg QA (2014) Three dimensional lumbar vertebral modelling. *Clinical Anatomy* **27 (6)**: 941 (Abstract).

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Author’s Declaration

This work contains no material that has been accepted for the award of any other degree or diploma in any university or tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text.

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Bahgat A Sami

28 /11 /2014

Preface

Thesis Intent and Structure

Lumbar anatomy is poorly understood. Detailed investigations of the structure and function have been performed, but agreement is yet to be achieved on either. This thesis is a succession of studies carried out with the general aim of clarifying the structure of the lumbar spine, correlating the anatomical details into a functional context, and discussing whether the comprehensive structural understanding gained thereby can be applied in a clinical environment. The thesis is organised into five chapters.

The first chapter aims to thoroughly review current background information regarding the lumbar mobility, stability and instability. This chapter demonstrates the need for a detailed quantitative model of the musculoskeletal lumbar structures. This understanding will be essential for better evaluation of the role of each structure. These outcomes could re-emphasise current concepts and disputes regarding spinal stability and low back pain among the multi-specialities of medical practices and the patients themselves.

The second chapter gives details of the samples and methods of investigation which were used in the study, and gross observation of the sets of the dry articulated lumbar vertebrae in order to document any degenerative changes and also to note the curvature shape of the lumbar articular facets. Similarly, all the specimens were observed grossly for any deformity or anatomical variation at different stages of dissection.

The Microscribe device constructs a three dimensional model of the lumbar articular facets. This allows calculation of the surface area and the orientation of the articular facets by the Rhinoceros X5 software (Robert McNeel and Associates, USA). The superficial and deep laminae of the posterior layer of the thoracolumbar fascia is photographed using a Canon camera (EOS, 40D). The direction of the fascial fibres is measured in the bilaminar plane using ImageJ software (Rasband, 1997-2014). Both laminae are also reconstructed by the Microscribe device to create a three dimensional model of the fascia. The direction of the fascial fibres is also measured by the Rhinoceros X5 software (Robert McNeel and Associates, USA). Serial cross dissections are taken to investigate the superficial myofascial connections between the thoracolumbar fascia and the superficial lumbar muscles. Similarly, the lateral raphe and the lumbar inter-fascial triangle are investigated by gross dissection.

The morphology and function of the lumbar extensor muscles and the intermuscular clefts are also documented. The types of entheses at the tendon-bone junction are studied histologically in order to correlate the morphology and function of the lumbar muscles. These histological findings are combined with the gross data to improve accuracy and also to decrease the subjectivity of the investigation.

The third chapter collects and summarises all the results into a comprehensive concept regarding lumbar stability. It is aimed at an enriched understanding of the orientation and surface area of the lumbar articular facets. These data have an important clinical implication: they may permit prediction of those facet joints which are at higher risk of developing degenerative joint diseases.

The focus of the study is widened to include the superficial myofascial structures. Morphological data about the thoracolumbar fascia is collected by both gross dissection and a three dimensional approach. The direction of the fascial fibres is achieved through visualization of the bilaminar layers of the fascia which was reconstructed in a virtual space. The morphological features of the lumbar muscles are collected from the cross sectional dissections. The foot prints of these muscles are documented to calculate the muscular attachment surface areas. The bulk of the multifidus muscle is observed to become larger gradually towards the inferior lumbar level. The two main types of the enthesis are identified: fibrous and fibrocartilaginous.

The fourth chapter compares the current findings of this study with previous disputed results of research which was undertaken to investigate lumbar stability and instability. The sagittalisation and degeneration of the lumbar facets are more predominant in the lower lumbar level. There may be an unintentional bias because the sample in the current study belongs to an old age group. Therefore, for future research it is highly recommended that samples from different age groups are selected.

The fifth chapter condenses all the conclusions and gathers the findings into an overall understanding of the lumbar function. It is aimed that with improved understanding, core stability may be improved. The current results within this thesis may provide a new outlook on the research of lumbar structure and function. It is anticipated that the functional hypotheses within this thesis will be tested in future investigations.

Chapter 1

Introduction

1.1 Core stability and low back pain

Spinal stabilization is the ability of the lumbopelvic skeleton to be stable and to retain the balance after unrest or movement (Haussler, 1999). This stability is greatly maintained by the muscular dynamic function. Also, static elements such as bone and other soft tissue contribute more or less to spinal stability. The bony skeleton also contains and protects two important neurologic functions: proprioception and nociception (Stokes *et al.*, 2000; Willson *et al.*, 2005). Spinal stability is achieved mechanically when the applied loads on the spine run tangentially to the sagittal vertebral curvature (Aspden, 1989). This balance allows the lumbar spine to support the weight of the upper body and/or any applied force without failure (Panjabi *et al.*, 1993).

Mogren and Pohjanen (2005) argued that there was limited data indicating that localized spinal instability could develop low back pain (LBP) during different physiological conditions such as pregnancy, obesity or post-operative damage. Also Lederman (2010) shed light on these dramatic physiological changes and agreed that these traumas to abdominal musculature are not likely to be detrimental to spinal stability or to predispose to lumbar pain. LBP, especially the chronic back pain, is the most frequent cause of major disabilities (Raoul *et al.*, 2003; Last and Hulbert, 2009). Regardless of cultural origin or ethnic diversity or physical fitness, there is up to 20% prevalence rate of LBP among athletes who are undertaking intensive strength training programmes (Hides *et al.*, 2008a).

Ehrlich (2003a) documented the occurrences of LBP in some countries which were dealing inappropriately with the entire management of LBP. Lots of cases of acute LBP that deteriorated to chronic LBP were iatrogenic. The overall lack of attention to back pain by both the governmental and medical institutes was blamed for this misperception. Furthermore, Ehrlich (2003a) claimed that LBP was mostly manipulated by alternative medicines, which consequently modified the general outcomes and so indirectly reduced the costs of absenteeism and medical care. Economically, chronic back pain is not merely a medical or psychosocial issue, but also preliminary to further problems related to the high associated costs of treatment, pensions and loss of workforce power (Reck, 2005).

Many debates and disputes concerning the evaluation and treatment of chronic LBP have been aroused. Most cases of LBP are due to non-specific causes which are usually self-limiting. However chronic LBP is more problematic. Despite the radiological diagnosis of intervertebral disc herniation, the underlying cause of LBP is not well-known. Eventually, neither a single diagnostic tool, nor a specific treatment, is superior to any others (Ehrlich, 2003b).

Mannion *et al.,* (2001) argued that some specific active muscle-training programmes have been relatively effective. Nevertheless, there were no studies which quantified evidence about physiological or anatomical changes in the back muscles. The findings elicited that these active programmes only support and encourage patients, rather than retaining any real muscular efficacy and so contradict the perceived validity of the manipulative therapy preferred by the patients. However, part of the improvement in strength after active therapy (in all groups) also appeared to be due to an increased neural activation of the trunk muscles. These positive effects should be transferable to the performance of everyday activities for which the same muscles are employed. Similarly, Ehrlich (2003a) cited that the WHO has outlined certain outcome criteria to be relied on to evaluate the worth of a treatment. Recently, gene therapy for preventive and therapeutic purposes on disc disorders ultimately may have brought hope to clinical practices (Biyani and Anderson, 2004). Last and Hulbert (2009) suggested that surgical evaluation should be considered after the failure of other non-invasive approaches.

The classical conception that LBP is caused by muscle hypoxia and intramuscular pressure-induced compartment inflammation, has been refuted (Kramer *et al.*, 2005). Alternatively, it had been suggested that other factors have to be included (Dehner *et al.*, 2009). Despite this, experiments on rats revealed that intramuscular blood flow was significantly lower and there was a higher intramuscular pressure in the back pain model rats. As a result these measures still support the role of tissue hypoxia and fatigue in causing inflammation and LBP in the lumbar para-spinal muscles of the rats.

In humans it has been suggested that muscular fatigue may contribute to LBP and spinal instability. Thereby, the neuromuscular system will recruit trunk muscle activity as a response to this instability (Granata and Gottipati 2008; Granata and

Orishimo, 2001; Granata *et al.,* 2001). This flexible recruitment of the neuromuscular system shows the strategy of the central nervous system to maintain the required spinal stability (Hashemirad *et al.*, 2009; McGill *et al.*, 2003). It was confirmed that there were motor changes in controlling the trunk muscles in patients with LBP (van Dieën *et al.*, 2003b). These data, beside the general knowledge of the importance of the abdominal wall for a stiff, stable back, give rise to certain beliefs which have been adopted in training programmes and exercises for both athletes and patients (Jull and Richardson, 2000; Richardson *et al.*, 2002; Lederman, 2010). The asymmetry in the thickness of the transversus abdominis muscle was detected only in patients with LBP as compared to normal individuals without LBP (Springer *et al.*, 2006).

1.2 Anatomy of the lumbar vertebrae

Several musculoskeletal soft and hard tissues integrate to form the anatomical basis of spinal stability. While genetic factors are directed toward regional adaptation of the vertebral column, the mineral content provides strength to the spine. Movement and spinal stability will be generated and supported by the lumbar musculature. These muscles have another mechanical role: they can absorb the axial loads. However, any muscular imbalance due to sustained forces or repeated tasks can produce serious lumbar spinal disorders (Gilchrist *et al.*, 2003; Prakash *et al.*, 2007).

The skeletal structure of the human (*Homo sapiens*) lumbar region is composed of five articulating vertebrae. They are identified by their position in the intact vertebral column. From superior to inferior, they are named as: the first, second, third, fourth and fifth lumbar vertebrae and can be abbreviated as L1, L2, L3, L4 and L5 respectively (Bogduk, 2005). The lumbar spines have a fundamental role in both stability and mobility. These spines provide stability while maintaining critical mobility, in addition the spines are protecting the integrity of the neural structures (Boszczyk *et al.*, 2001). The lumbar facet (zygapophyseal) joints have a vital task in load transmission between the lumbar vertebrae and have a fundamental role in rotational movements (Panjabi *et al*., 1993). Correlation between the function of these joints and LBP is a longstanding debate (Panjabi *et al.*, 1993; Dahl *et al.*, 2013).

The lumbar vertebrae are irregular bones which can be divided into three functional parts: the anterior part (vertebral body), the posterior parts (laminae and its processes) and the middle segment (pedicle) which connects the posterior parts to the anterior one (Figure 1.1). The vertebral body is primarily responsible for the weight-bearing task of the vertebra and is well specialised for this purpose. It has flat superior and inferior surfaces that are committed to resisting any vertically applied loads. All the elements of the posterior parts, the laminae, the articular processes and the spinous processes, provide areas for muscle attachments (Bogduk, 2005).

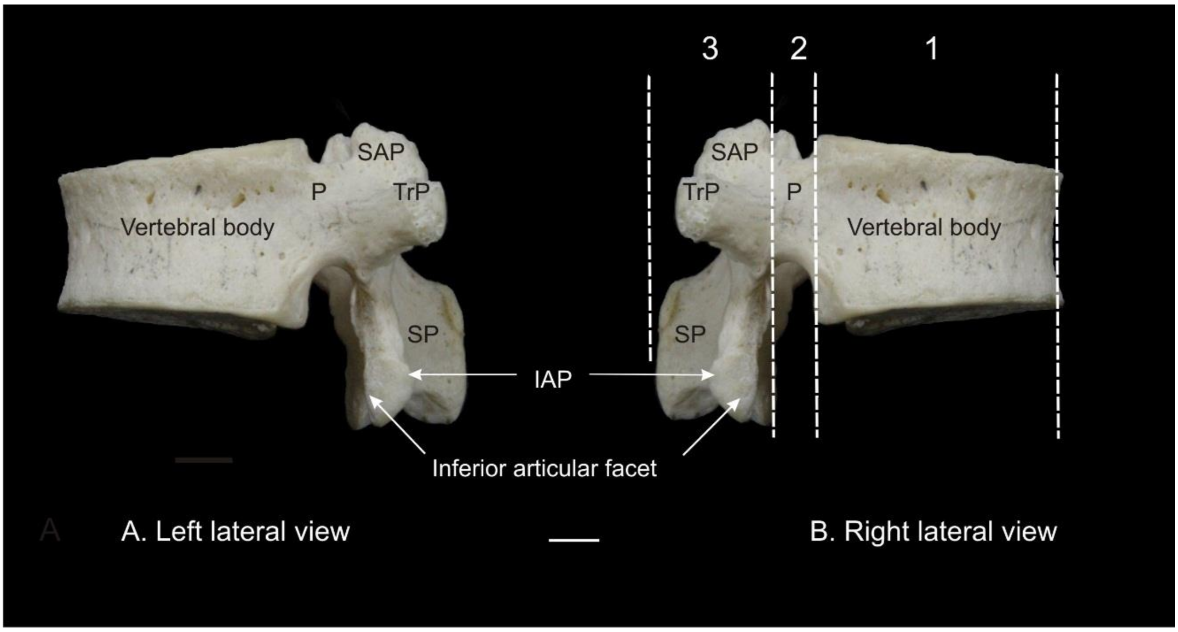

Figure 1.1 The lateral sides of the of the first lumbar vertebra (L1). A- Left lateral view shows the different parts of the vertebra: the superior articular process (SAP), the transverse process (TrP), pedicle (P), vertebral body, the inferior articular facet (IAF). Inferior articular process (IAP) and the spinous process (SP). B- Right lateral view shows the three functional parts of the vertebra; anterior part (1) which is the vertebral body; the middle part (2) which is the pedicle (P); while the posterior part (3) consists of two superior and two inferior articular processes, two transverse processes, the two laminae (not obvious here) and the spinous process. Scale bar = 1cm.

The pedicle extends posteriorly from the superior part of the posterior of the vertebral body on each side. The pedicles are the only connecting bones between the posterior elements and the vertebral bodies (Bogduk, 2005). All forces sustained by any of the posterior elements are eventually translated towards the pedicles, which then transmit the benefit of these forces to the vertebral bodies. Therefore, muscular action is transmitted to the vertebral body through the pedicles, which act as levers and thereby, the pedicles are subjected to a certain amount of bending (Bogduk, 2005). The laminae are two plates of bone that project from each pedicle towards the midline. The spinous process is the most posteriorly bony prominent structure that can be palpated on the back midline, which projects posteriorly from the junction of the two laminae. A cylinder-like mass extends upwards and enlarges into a specialised mass called the superior articular process on each side. Similarly, a mass of bone buds from the pedicle downward to form the inferior articular process. On the inner surface of each superior articular process and on the outer side of each inferior articular process there is a smooth area of bone which is covered by articular cartilage in the intact spine. These areas are known as the superior articular facets and inferior articular facets, respectively (Figure 1.2).

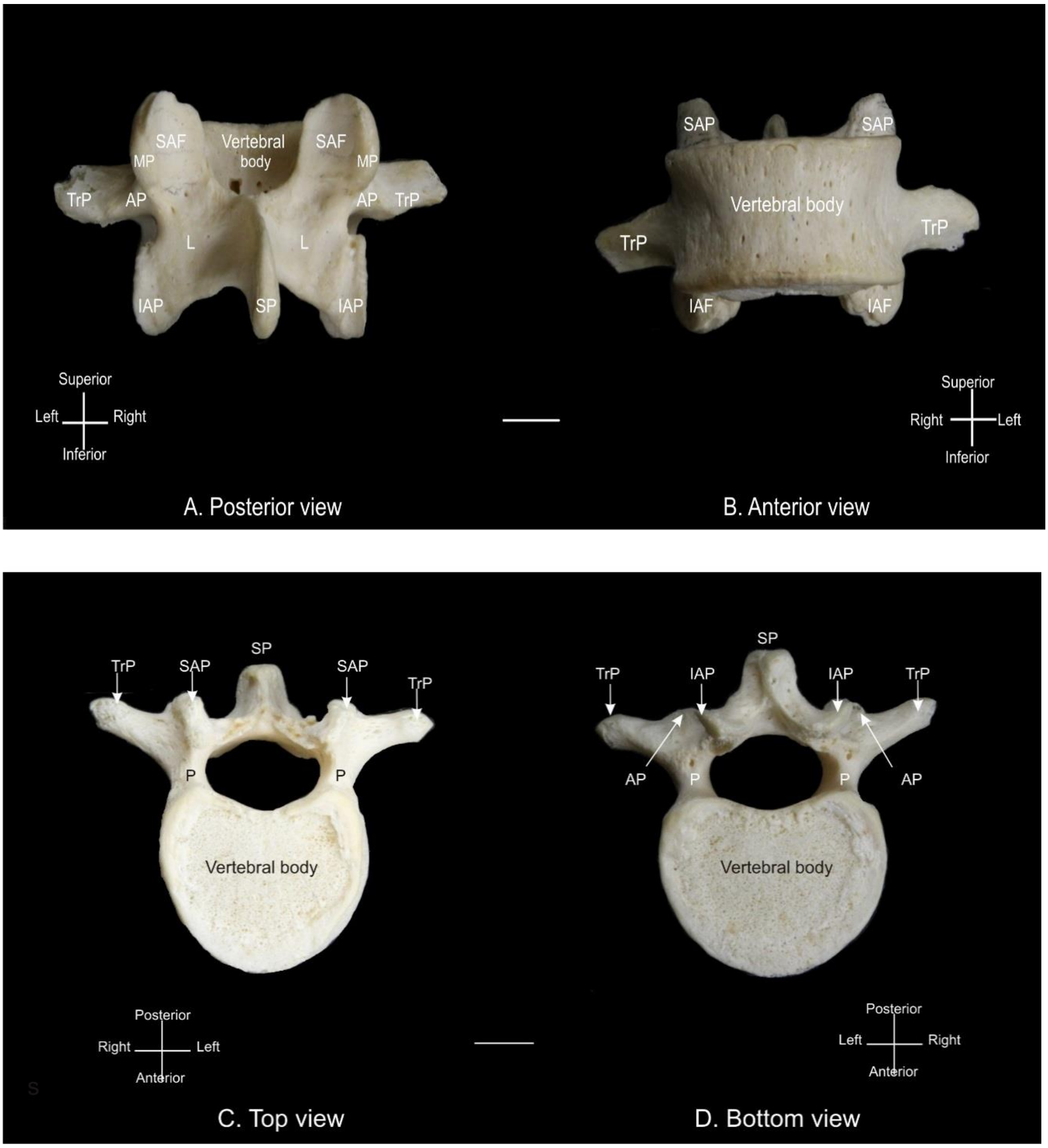

Figure 1.2.The parts of a typical lumbar vertebra. Posterior view (A), anterior view (B), superior view (C) and bottom view (D): accessory process (AP), inferior articular process (IAP), inferior articular facet (IAF), lamina (L), mammillary process (MP), , superior articular facet (SAF), superior articular process (SAP), spinous process (SP), transverse process (TrP), vertebral body. Scale bar = 1 cm

Extending laterally from the junction of the pedicle and the lamina on each side, is a flat, rectangular bar of bone called the transverse process, so named because of its transverse orientation. Near its attachment to the pedicle, each transverse process bears on its posterior surface a small, irregular bony prominence called the accessory process (Bogduk, 2005). Another small smooth distinguishable bony mass known as mammillary process is found on the posterior margin of the superior articular process (Figure 1.2 D and F).

When any two consecutive lumbar vertebrae are articulating, they form three joints. One is formed between the two vertebral bodies known as the intervertebral joint. The other two are formed by the articulation of the superior articular process of one vertebra with the inferior articular process of the vertebra above. Officially, these joints which are formed between the processes are named as zygapophysial joints (Figure 1.3).

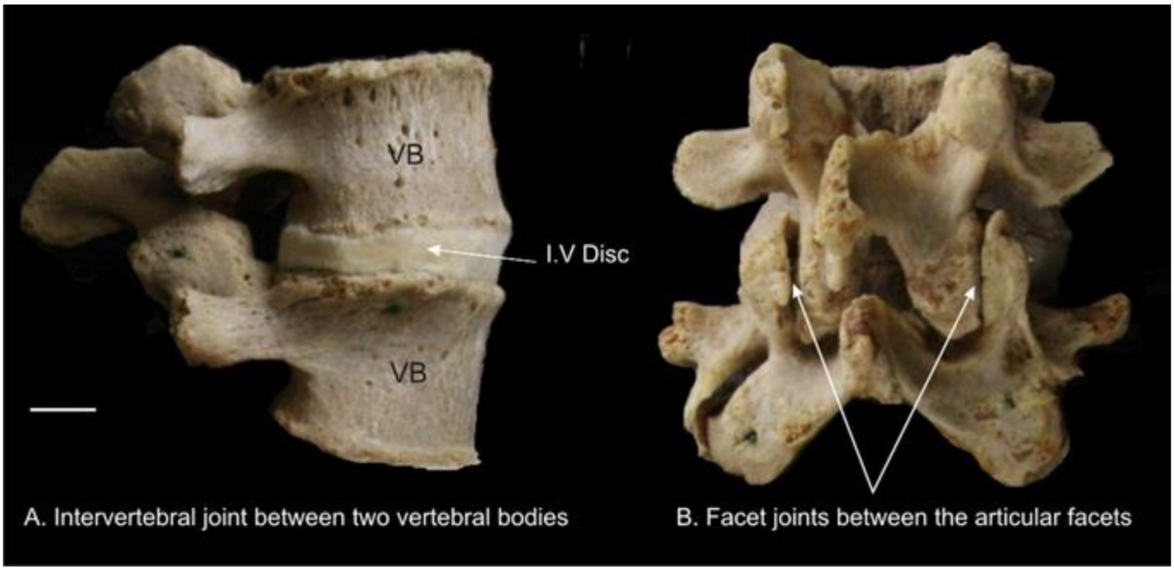

Figure 1.3 The joints between two lumbar vertebrae. A: the intervertebral joint and B: the articular facet (zygapophysial) joint. Scale bar = 1 cm

The word 'zygapophysial' comes from two Greek words, apophysis, meaning outgrowth, and zygos, meaning yoke or bridge (Nomina Anatomica, 1989). The zygapophysial joints are often known as facet joints (FJ), so the term facet joint will be used throughout this study to refer to the zygapophysial joints, because it is more popular worldwide, especially in American literature (Bogduk, 2005). The FJ consist of the inferior articular facet of one vertebra articulating with the superior articular facet of the vertebra below. The lumbar FJs have a different shape, size and orientation to the frontal (coronal) plane. The superior articular facet could be flat or curved, and its angulation may vary from 0 to 90 degrees (°) to the coronal plane.

In the thoracolumbar region of the vertebral column there is abrupt sagittalisation of the superior articular facet from the thoracic to the lumbar region of the vertebral columns. This sagittalisation is due to the change in the direction of weight transmission through the FJ (Pal and Routal, 1999). The superior articular facet is eventually fused with the mammillary process (tubercle). Thus the superior articular facet of the lumbar vertebrae assumes a concave shape which is directed as a posteromedial orientation (Pal and Routal, 1999). The superior and inferior articular process possesses a true specific three-dimensional surface. Therefore, any investigations regarding the mechanical function of the FJ could be achieved only by the three-dimensional approach (Dahl *et al.*, 2013). At the lower lumbar levels the sagittalisation is diminished and the FJ are oriented more coronally (Vora *et al*., 2010). This may provide more resistance to shear forces and prevent anterior displacement of the lumbar spine. At the superior lumbar levels the FJs are more sagittally directed and thus they limit rotational movement but do not provide much resistance to the anterior displacement of the lumbar spine. Furthermore, symmetrical orientation is not found between the right and left FJs at the same lumbar vertebral levels (Vora *et al*., 2010).

1.2.1 The lumbar facet joints and low back pain

The lumbar FJs have been recognized for many years to be an important source of chronic LBP with sciatic pain radiation (Carrera and Williams, 1984). Lumbar FJ mediated pain accounts for a considerable portion of chronic LBP (Bogduk, 1995). Perhaps the excessive capsule stretch activates nociceptors, which may lead to prolonged neural discharges. In the longstanding condition it can even cause damage to the joint capsule. This overstretching of the joint capsule is most likely the possible cause of persistent pain (Cavanaugh *et al.*, 2006). FJ mediated pain was 52% prevalent in the elderly and up to 30% in adults. This suggested that FJ as a pain generator was significantly prevalent in all patients complaining of chronic LBP regardless to their age (Manchikanti *et al.*, 2001). This association could be the reason behind why aging people are more prone to degenerative spondylolisthesis (Gluck *et al.*, 2008).

Hitherto, no specific clinical or radiological findings of FJ mediated pain have been reported (Dreyer and Dreyfuss, 1996). Excessive facet capsular stretch may also be a possible cause of persistent pain in patients with LBP (Cavanaugh *et al.*, 2006). Hence, a better understanding of FJ orientation and shape is therefore needed to better inform clinical interpretation of patient data and imaging. Moreover, there is no unique radiological modality such as plain X-ray or CT in diagnosis of abnormal facet orientation (Cox *et al.*, 1991). Therefore, both CT and MRI scans should be done for patients with degenerative FJ diseases to get a comprehensive evaluation of the facets' morphological features (Xu *et al.*, 2014).

1.2.2 The curvature shape of the facets

The orientation and shape of the lumbar FJ play an important role in stabilizing the lumbar spine by limiting spine mobility (Holzapfel and Stadler, 2006). The importance of the curvature has been widely ignored in previous work done on the facet orientation. The shape of the joint also adds additional resistance: C-shaped facets usually have a greater surface area so provide greater resistance to forward dislocation than J-shaped facets (Vora *et al.*, 2010). Understanding how the FJ shape and orientation changes throughout the lumbar spines is very important clinically when considering back function and dysfunction.

1.2.3 Facet orientation and tropism

Facet tropism (FT) can be found when the difference in angulation between the right and left facet orientation of the same vertebra is more than 10° (Chadha, 2013). It can be classified as mild, moderate or severe tropism (Dai, 2001). However, the clinical importance of facet tropism is still under dispute.

No significant evidence was noted about the importance of FJ orientation and tropism in patients with disc herniation. This finding was revealed by both CT analysis of the inferior three lumbar levels (Ko and Park, 1997) and a similar MRI study (Kunakornsawat *et al.*, 2007). In addition, another study comparing the facet orientation and tropism in adult and adolescent patients did not find a significant difference in facet orientation between herniated discs and normal discs. The only significant data about disc herniation was noted in adults at the L4-L5 level (Lee *et al.*, 2006a; Lee and Lee, 2009).

Similarly, no specific relation was confirmed between facet tropism and osteoarthritis (Linov *et al.*, 2013). In contrast, a negative correlation of the coronal orientation of the L4-L5 FJ to age was documented (Wang and Yang, 2009). This negative relation could explain why the elderly people are more susceptible to osteoarthritis and degenerative spondylolisthesis of the L4-L5 FJ.

It was concluded that even FT is a normal feature in humans, yet it varies along the thoracolumbar spine (Murtagh *et al.*, 1991; Masharawi *et al.*, 2005). Therefore, additional longitudinal studies are needed to understand the causal relationship between facet joint orientation and osteoarthritis. To the contrary, other evidences claimed that there is a positive association between the FJ sagittalisation and OA (Liu *et al.*, 2013). Previous studies documented that up to 40% of elderly patients had variable degrees of loss of the coronal orientation. This change was strongly associated with osteoarthritis of the lumbar FJ (Fujiwara *et al.*, 2001; Vora *et al.*, 2010). These changes decreased FJ resistance against anterior displacement, and so increased vulnerability to degenerative spondylisthesis (Vora *et al.*, 2010).

A previous study revealed that the lumbar FJ was not the principle support structure in extension movements (Haher *et al.*, 1994). The alternative structural pathway of loading transfers is to the annulus fibrosus and the anterior longitudinal ligament. Despite not producing acute disability, it will shift loads to the disc and possibly speed up its degeneration (Haher *et al.*, 1994). This means that the lumbar FJ is not the principal supporting structure in lumbar extension. The sagittal orientation of the L4-L5 FJ was positively correlated to age. This may explain the pathogenesis of the risk of degenerative spondylolisthesis in elderly people (Gluck *et al.*, 2008).

This asymmetry of facet orientation between left and right facet joints is postulated as a possible cause of disc herniation. MRI analysis of data from patients who had disc herniation at L4-L5 level and at L5-S1, revealed an association between facet tropism and lumbar disc herniation. This association was significant only at the L5-S1 motion segment but not at the L4-L5 level (Chadha *et al.*, 2013). However, previous findings suggested that severe facet tropism is associated with increased disc bulge at L4-L5 in older age patients (Do *et al.*, 2011) and was found to be significantly associated with severe facet degeneration at this active segment motion (Kong *et al.*, 2009), whereas other previous results have totally denied any relation between the tropism in facet joint degeneration and have revealed that other factors like age, spinal level and facet orientation were more important (Grogan *et al.*, 1997). So the ongoing debates regarding the importance of facet tropism remain unclear.

In a combined study by CT scan and MRI to measure FJ tropism and degeneration respectively, cartilage degeneration in the joint was not associated significantly with tropism, as compared to joints without tropism. Subcortical sclerosis was slightly greater in joints with tropism. In contrast, sclerosis and cartilage degeneration were significantly related to age and spinal level. Therefore, age, spinal level, and facet sagittalisation are more important factors than tropism in facet joint degeneration (Grogan *et al.*, 1997). Tropism was defined as the difference in FJ orientation between the right and the left side of more than 10° (Chadha *et al.,* 2013).

Facet tropism has been considered previously as a pain generator in patients with LBP (Vora *et al.*, 2010). It was observed that FJ in individuals with tropism rotated towards the side of the more coronal (oblique) facet (Cyron, 1980). This rotation could in turn place extra load (stretch) on the capsular ligament of the FJ and lead to the release of substance P. This suggests that facet tropism may lead to degenerative change in the FJ (Haig *et al.*, 2006), and also intervertebral disc degeneration (Kong *et al.*, 2009). However, another study revealed that at the L3-L4, L4-L5, and L5-S1 spinal levels the facet joints orientation with osteoarthritis were more sagittally oriented than those without osteoarthritis, but the difference was statistically significant only at L4-L5 spinal level ($P = 0.0007$). In addition, facet orientation was significantly associated with degenerative spondylisthesis, while there was no association observed between the facet tropism and facet joint osteoarthritis or degenerative spondylisthesis at any spinal level (Kalichman *et al.*, 2009). Similarly, there was sagittalisation of the articular facets in all lumbar levels in the patients who had degenerative spondylolisthesis. The greatest difference was at the level of the L4 and L5 vertebrae ($p = 0.00001$). There was no association documented between increased facet tropism and disc degeneration. Furthermore, the increased facet sagittalisation at levels without any spondylolisthesis change at those levels, suggests anatomical variation rather than a secondary result of spondylolisthesis of the L4-L5 (Boden *et al.*, 1996b). Similarly, another study could not find any association between facet orientation, tropism, and degenerative spondylisthesis (Kalichman *et al.*, 2010).

1.2.4 The surface area of the articular facets

The surface area of the FJ is an important factor for better understanding FJ physiopathology. FJ area has been reported to increase gradually towards the inferior lumbar levels (Otsuka *et al.*, 2010). This increase in the area of the facet is perhaps secondary to the greater load translated or applied to the lower lumbar segments. Additionally, the facet area could be increased with age and in patients with LBP due to joint osteoarthritis, compared with normal individuals. C-shaped facets have a larger area than the J-shaped variety (Vora *et al.*, 2010).

Other parameters important in lumbar spinal morphology are the inter-facet distance and lumbar lordosis. Additionally, association with L5 spondylolysis was investigated by lumbar CT scans of patients and control. There were significant differences ($p<0.05$) of inter-facet distance at the L3, L4, and L5 level. The L5-S1 was more lordotic in the patients group (Chung, 2012). These findings revealed that the orientation of the articular facets of more than 43° was significantly associated with degenerative spondylolisthesis (Tassanawipas *et al.*, 2005).

The lumbar articular facets have variable anatomic orientation which plays an important role in the stability and mobility of the lumbar spine. There is no doubt that the FJ play an important role in spinal load transmission and are crucial for rotational movements (Tischer *et al.*, 2006). In addition the variable size and shape of the FJ may influence spinal stability (Dahl *et al.*, 2013). Despite the importance of FJ anatomy in a practical setting, few studies have been done quantifying FJ geometric data. Clinically, the role of facet joints as a possible source of LBP is seen as controversial and at present is not sufficiently investigated. Therefore, an informed knowledge of this subject could be useful in improvement of diagnostic techniques and in the prevention of lumbar FJ degenerative diseases and LBP, and could contribute to the design of future study targets. Furthermore, several important applications could be emphasised by the quantification of vertebral articular facets into a three dimensional database (Panjabi *et al.*, 1993).

1.3 The superficial lumbar myofascial tissues

In the previous several decades a great deal of attention had been given to the importance of core stability, and extensive research has also have been carried out on the thoracolumbar region. Most of the work in this area has focused on intrinsic vertebral supports, with few looking superficially (Vleeming *et al.*, 1995; Bogduk and Yoganandan, 2001). Only the most recent studies have looked at modelling peripheral interactions between these soft tissues (Barker *et al.*, 2004b; Nuckley and Ching, 2006). The movement and stability of the low back region is dependent on distributing the balance of forces via the myofascial planes associated with the thoracolumbar fascia (TLF). This fascia (passive element) is located at a common connection of several trunk muscles with limb muscles (active element) such as latissimus dorsi, transversus abdominis and gluteus maximus muscles (Mclain, 2006).

Several musculoskeletal soft and hard tissues integrate to form the anatomical basis of spinal stability (Grifka *et al.*, 1998; Gilchrist *et al.*, 2003). The TLF consists of three layers: anterior, middle and posterior layers. Basically, these layers subdivide and enclose the lumbar para-spinal muscles (Macintosh and Bogduk, 1987; Pope and DeVocht, 1999). The anterior layer encases the psoas major and quadratus lumborum muscles while, the posterior layer surrounds the erector spinae muscle and its aponeurosis. The middle layer separates between the erector spinae and the quadratus lumborum muscles (Izzo *et al.*, 2007).

The posterior layer is the most active layer in supporting the lumbar muscles. It consists of a superficial and a deep laminae. Moreover the fibres of the superficial lamina of the posterior layer pass inferiorly and medially: nearly at a right angle to the direction of the deep lamina's fibres (Bogduk and Twomey 1987; Bogduk, 1991). The superficial lamina is the direct continuation of the aponeurosis of the latissimus dorsi muscle and is continuous superiorly with the rhomboid muscles. The direction of the superficial lamina of the posterior layer of the TLF has an angle range between 15-30° below horizontal from superior to inferior lumbar vertebral levels (Tschirhart *et al.*, 2007). These fibres run from the latissimus dorsi aponeurosis inferomedially to the Lumbar spinous processes, whereas the deep lamina is composed of bands of fibres attached to the thoracic and upper lumbar spinous processes and descend inferolaterally. The aponeurotic fibres of the deep lamina are best developed from the L3 and downward. The deep fibres run almost parallel to each other at an angle of 20-30° below horizontal. These fibres arise from the lumbar spinous processes and descend to the iliac crest inferiorly and the muscular raphe laterally (Tschirhart *et al.*, 2007). Both laminae form a continuous retinaculum over the back para-spinal muscles (Resnick *et al.*, 1997; Tschirhart *et al.*, 2007). Thus, they form a retinacular sheath known as the para-spinal retinacular sheath. The lateral raphe is formed at the lateral border of the para-spinal retinacular sheath, where the sheath meets the aponeurosis of the transversus abdominis muscle. This raphe is a thickened complex of dense connective tissue due to the presence of the lateral inter-fascial triangle (Bellini *et al.*, 2007). The posterior layer of the TLF crosses to the contralateral side forming a decussating structure, which may allow a greater freedom in anterior flexion (Prestar, 1982; Bogduk, 1991).

A three-dimensional model of the superficial lamina was reconstructed and its results counteracted the classic emphasis regarding the arrangement of the deep fascia as an irregular, dense, connective tissue layer. Three sub-layers of the superficial lamina of the posterior layer have been recognized. Each had different morphological features and the angle between the collagen fibres of the superficial and intermediate sub-layers was 78° (Benetazzo *et al.*, 2011).

In patients with LBP, investigations could not identify specific neural endings in the poster layer of the TLF and revealed a deficient innervation due to inflammation of the fascia (Rade *et al.*, 2012). However, most recent findings suggests that the TLF is most sensitive to chemical stimulation, thus making it a main source of generation of nonspecific LBP (Schilder *et al.*, 2014).

The TLF contributes to the supraspinous ligament. This contribution serves as an accessory ligament that anchors the L2 - L5 spinous processes to the ilium and resists flexion of the lumbar spine (Barker and Briggs, 1999). The anti-flexion work of this ligament is greatly reinforced by the contraction of the back muscles and anterolateral abdominal wall muscles (Barker and Briggs, 1999; Bellini *et al.*, 2007; Tschirhart *et al.*, 2007; Loukas *et al.*, 2008). The superficial and deep laminae of the posterior layer are more extensive superiorly than previously documented. This may be of clinical importance in certain tests in the management of LBP such as the slump and "nonorganic" tests. However, these superior extensions were of variable thickness (Barker and Briggs, 1999).

The role of the TLF has been documented since the latter half of the previous century. Much evidence suggested that the TLF can be tensed by the abdominal and limb muscles to reduce and distribute the load at the lumbar intervertebral joints. Thus this fascial tension will ensure the integrity of the spinal machinery (Gracovetsky *et al.*, 1985; Gracovetsky and Farfan, 1986; Gracovetsky, 2008; Gatton *et al.*, 2010). The role of the TLF in restricting the radial expansion of the erector spinae muscles had been documented. This restriction may increase the tension created during the contraction of the erector spinae muscle by up to about 30% (Hukins *et al.,* 1990). In addition, the presence of neural elements in the TLF supported the hypothesis regarding the neurosensory role of the TLF in spinal stability (Yahia *et al.*, 1992).

There are lot of arguments and controversies regarding the exact role and contribution of the TLF in lumbar spinal stability and lower limb mobility. Tesh *et al.*, (1987) concluded that the abdominal muscles act through the TLF to resist flexion. This fascial tension was of a similar magnitude to that offered by a raised intra-abdominal pressure. Thus it was suggested that the stabilizing action of the TLF was less than had been thought previously. However, until recently artificial bracing in the form of a weight belt has been recommended to provide externally enhanced stability (Grenier and McGill, 2007).

In contrast, this has been opposed by several studies that contradict the previous findings and clarify the positive role of the fascial tension on both trunk balance and the lower extremity mobility (Bednar *et al.*, 1995; Barker and Briggs, 1999; Barker *et al.*, 2004b; Willson *et al.*, 2005). Moreover, focus on the posterior layer of the TLF and the attachment of its superficial lamina to the gluteal muscles, sacrum and ilium, has been identified as being more involved in generating tension in lifting than the previous literatures had assumed (Vleeming *et al.*, 1995; Willson *et al.,* 2005; Barker *et al.,* 2014).

In individuals with LBP the viscoelastic property of the TLF collagen has a direct role in the manner that muscles of the lumbosacral region are used and how forces were translated from the foot to the upper limbs. Keeping the lumbar curvature in the balanced stable condition is the key element to controlling the normal distribution of forces between these myofascial structures in the case of back injuries (Gracovetsky, 2008). Additionally, there was about 20% reduction in the

TLF shear strain in individuals with chronic LBP (Puttlitz and Diangelo, 2005; Langevin *et al.,* 2011).

Furthermore, the myofascial connections between the TLF and the surrounding superficial muscles of the back provide access for the latissimus dorsi muscle and the transversus abdominis muscle to apply tension on the posterior and the middle layers of the TLF. The transversus abdominis muscle may apply low levels of tension which may affect only the inter-segmental vertebral movement (Barker *et al.*, 2004b).

A better understanding of the structure of this multipart myofascial junction is crucial for mechanical investigation and implementation of the effective reintegration of individuals with LBP (Mclain, 2006). Therefore, this study was structured to describe the anatomy of the superficial layer of the TLF, and specifically the connections with gluteus maximus, latissimus dorsi, the transversus abdominis and internal oblique muscles. These connections may function in the distribution of forces which are generated by these muscles along the posterior layers of the TLF (Gracovetsky *et al.,* 1985; Tesh *et al.,* 1987; Yahia *et al.,* 1992; Gatton *et al.,* 2010). This study could reveal more and so may answer the enquiries raised from the continuing debate and unresolved arguments regarding the exact role and contribution of the TLF in lumbar stability and lower limb mobility.

1.3.1 The latissimus dorsi and the gluteus maximus muscles

In vitro, the posterior layer of the TLF could be tensed by a variety of lumbar muscles. The force of the latissimus dorsi, gluteus maximus and erector spinae muscles can be translated via the superficial lamina of the TLF. The deep lamina can be tensed by contraction of the biceps femoris (Vleeming *et al.*, 1995). In addition, distal to the level of L4, tension in the posterior layer was transmitted to the contralateral side (Vleeming *et al.*, 1995). The compressive forces of the gluteus maximus muscle can cross the sacroiliac joint through its bony and fibrous attachments. The fascicles of the gluteus maximus muscle were documented to be originated from the gluteus medius fascia, TLF, erector spinae aponeurosis, ilium, sacrum, coccyx, dorsal sacroiliac ligament and sacrotuberous ligament. The translation of these forces may assist in effective load transfer between lower limbs and the trunk (Noailly *et al.*, 2007).

The latissimus dorsi aponeurosis forms and/or continues with the superficial lamina of the posterior layer of the TLF. This extension is inserted into the tips of the spinous process of L1-L3 and contributes to the constitution of the supra-spinous ligament via this insertion. However, the supra-spinous ligament is absent below the L4 level. The collagen fibres of the superficial lamina of the posterior layer of the TLF continue to cross the midline to interlace with the contralateral side (Prestar, 1982; Bogduk, 1991). It was suggested that the selection of foot placement is an important factor for the effective strengthening of the latissimus dorsi muscle (Yoo *et al.*, 2013).

1.3.2 The spinal ligaments

Normally, the inter-spinous ligament is absent below the level of L4. It is most likely that the erector spinae muscle replaces the deficient inter-spinous ligament in this region to maintain the spinal stability. The TLF crosses to the contralateral side forming a decussating structure, which may allow a greater degree of ventral flexion, as the inter-spinous ligament restricts the ventral flexion of the lumbar spine (Prestar, 1982; Bogduk, 1991). This restriction is consistent with that of the porcine spinous ligamentous complex which is the largest contributor (40%) to the resistance of flexion motion (Gillespie and Dickey, 2004).

Histologically, the inter-spinous ligament and supra-spinous ligament are mainly collagenous. Furthermore, the inner fibres are oriented parallel to the spinous process, whereas those in the outer layer are directed posterocranially (Yahia *et al.*, 1990b). Presumably, these ligaments may transmit load from the TLF to the lumbar spine, so they may contribute to spinal stability (Yahia *et al.*, 1989; 1990a). Also Johnson and Zhang (2002) confirmed that the inter-spinous and the supra-spinous ligaments had musculotendinous and aponeurotic features in the thoracolumbar region.

Only 10% of the inter-spinous ligament rupture cases were associated with para-spinal muscles injuries such as inter-spinalis and multifidus muscle (MF) degeneration. No single radiological imaging modality is sufficient for a reasonable and reliable diagnosis of ligament rupture and muscle degeneration (Alam, 2002; Kliewer *et al.*, 1993). Thus, occasionally, these musculoligamentous findings could be the only abnormal features noted on MRI films of the lumbosacral spine and may theoretically be a source of LBP (Jinkins, 2003). Similarly, the damage to the inter-spinous ligament could be due to surgical interventions such as in spinal fixation which can alter the ligamentous biomechanical features, perhaps producing LBP later on (Kotani *et al.*, 1998).

Degenerative changes and calcification were found in most of the inter-spinous ligaments obtained from patients with disc rupture. The chondrocytes had replaced the fibroblasts and also several necrotic areas were noted (Yahia *et al.*, 1989). Moreover, several incidences clearly confirmed the presence of sensory free nerve endings (nociceptors) in the inter-spinous ligament and the longitudinal ligament of patients with discogenic LBP (Yahia and Newman, 1991). Controversially, Bednar *et al.*, (1995) confirmed the innervations deficiency and the presence of focal calcification within the TLF in patients with chronic LBP. Mechanical strength of lumbar posterior spinal ligaments shows gradual weakness with age and facet degeneration, (Iida *et al.*, 2002). In contrast, ligamentous stiffness powerfully influenced the mechanical capacity of the spinal motion unit (Zander *et al.*, 2004).

The neurologic feedback mechanism is based on evenly and well-distributed innervations throughout the spinal ligaments. There is a symmetrical distribution between the right and the left sides (Yahia and Newman, 1989; Jiang *et al.*, 1995). Contrarily, any neural degeneration which interferes with this proprioceptive neurologic reflex may cause adolescent idiopathic scoliosis (Rivard *et al.*, 1993). The superior costotransverse ligament is the most important ligament for the lateral spinal stability (Jiang *et al.*, 1994). Significantly, there were fewer free nerve endings in the lateral spinal ligaments (Jiang *et al.*, 1997), however no changes have been reported regarding the collagen biochemistry in the spinal ligaments of patients with idiopathic scoliosis (Venn *et al.*, 1983).

1.3.3 Viscoelastic tissues

Human resting skeletal muscle tone is an intrinsic passive myofascial viscoelastic tension which acts inseparably from fascial tissues and ligamentous structures which are all integrated within networks under tension (Masi and Hannon 2008). Thus viscoelastic tissue is one of the most important components of spinal stability (Solomonow, 2011). Immediate post static work measures underscored a significant decrease in the stabilizing function of viscoelastic tissues and muscular activity. Consequently, the spine will be unstable and highly susceptible to future injury (Williams *et al.*, 2000; Youssef *et al.*, 2008; Le *et. al.*, 2009).

The viscoelastic property of the TLF collagen has a direct role in the manner in which muscles of the lumbosacral region are used and how forces are translated from the foot to the upper limbs. Keeping the lumbar curvature in ae balanced stable condition is the key element to controlling the normal distribution of forces between these myofascial structures in cases of back injuries (Gracovetsky, 2008). TLF limits the radial expansion of the erector spinae muscle and might increase the contractile power generated during erector spinae muscle contraction by up to about 30% (Galbusera *et al.*, 2011). The distribution and the density of the bone minerals within the bone are the most important factors in determining bone quality and strength. Bone mineral density increases gradually inferiorly to S1 vertebra. Specifically, the maximum density level is located in the pedicles (Lu *et al.*, 2000).

There was no dispute that TLF provides a means of muscular attachment to the lumbar spine for several muscles such as the transversus abdominis, latissimus dorsi, gluteus maximus and internal oblique muscles (Gatton *et al.*, 2010). The distribution and balance of the forces via the myofascial planes associated with the TLF remains a matter of controversy and there is little information about the role of the interactions between these superficial myofascial tissues that contribute to the lumbar spinal stability.

1.4 Anatomy of the lumbar musculature

The human vertebral column has three primary functions: the protection of the spinal cord, bearing load and weight, and keeping flexible movement. The lumbar spinal skeleton provides the structural support. The spinal musculatures and ligaments produce complex and balanced vertebral movements (Haussler, 1999). The extensor muscles of the lumbar region provide a great degree of spinal stability and play an important role in controlling motion (Cornwall *et al.,* 2011). The lumbar para-spinal muscles are composed of two main groups: the deep group called transversospinalis muscles such as the MF, rotatores, inter-spinalis and intertransversarii muscles. The superficial group is composed of the erector spinae: iliocostalis, longissimus and spinalis. The deep muscles are attached to the lumbar vertebrae, controlling fine movements and so stabilising the spine (Hansen *et al.*, 2006; Ward *et al.*, 2009; Cornwall *et al.*, 2011), while the superficial erector spinae muscles are covering a large area of the spine and play more vigorous role in spinal mobility (Macintosh and Bogduk, 1991; Hansen *et al.*, 2006).

The musculature of the lumbar spine is of primary importance in the control of spinal mechanism efficiency (Gracovetsky, *et al.*, 1985). Female trunk muscle geometry differs significantly from that of the male. This should be considered in the development of biomechanical models of the torso (Jorgensen *et al.*, 2001; Marras *et al.*, 2001). The muscles that attach directly to the spines are classified as the primary lumbar muscles and they control spinal motion. The secondary lumbar muscles are responsible for lumbar gross movements without a direct insertion into the lumbar spines (Pope and DeVocht 1999), while Kim and Kim (2008) divided the lumbar muscles as deep trunk muscles, such as the MF muscle, intertransversarii and rotatores muscles, and the superficial muscles, such as the erector spinae muscles.

Other studies have investigated the biomechanical structure of the muscles. A large quantity of Type I muscle fibres, which had a larger diameter, were found in the thoracolumbar back muscles, whereas the diameter of type II muscle fibres was smaller and they were less common. In lumbar disorders, there is selective atrophy, and reversible pathological damages in type II fibres have been underlined (Ng *et al.*, 1998; Renkawitz *et al.*, 2006). Substantial asymmetrical differences in activity between the right and left axial rotation were verified in external oblique, internal oblique, latissimus dorsi and iliocostalis lumborum muscles, whereas no difference was shown in rectus abdominis and MF muscles (Ng *et al.*, 2001). The most common reported spinal deformity is scoliosis. Generally, it is unbalanced compression on the vertebral endplates which predispose the vertebral column to such deformities. Consequently, there will be malfunctioning abdominal musculature and, hence, as a compensatory mechanism will lead to lumbar para-spinal over activity (Lam and Mehdian, 1999).

Passive muscle tone helps to maintain comfortable and relaxed standing body posture with minimally increased energy costs as much as possible and for prolonged durations without fatigue (Masi and Hannon, 2008). In spite of that, during the prolonged static work, even under low loads or tolerable work, it cannot be designated as risk-free performance. In such circumstances it may end in muscle spasm after more than 24 hours, and even neuromuscular disorders later on (Kirkaldy-Willis, 1992; Solomonow *et al.*, 2003; Le *et al.*, 2009).

The repetition of lifting tasks for a specific duration can change the loading pattern, which may appear as low back disorders (Marras and Granata, 1997; Granata *et al.*, 2004). Therefore reassessment of spinal stability in patients with LBP should consider the pace, duration and direction of movement to improve the workplace design (Williams *et al.*, 2000; Granata and England 2006; Lee *et al.*, 2008).

Many studies have concluded that antagonistic co-contraction of the para-spinal muscles is necessary to increase trunk stiffness and hence to stabilize the spine during flexion (Granata and Marras, 1995; Marras *et al.*, 1998; Lee *et al.*, 2006b; 2007). This is approximately twice the value of co-contraction during extension, i.e. 28% and 13% of the total muscle forces respectively (Granata and Marras, 2000; Granata *et al.*, 2005). However, in submaximal flexion and extension tasks there was no increased activity of the co-contraction of antagonist muscles (McCook *et al.*, 2009). In life the position of moderate flexion is to be ideal when a strong compressive forces is applied onto the lumbar spine (Adams, 1994). This conclusion was achieved by comparing different ranges of flexion / extension movements *in vivo* and *in vitro*.

The intra-abdominal pressure and antagonistic activation of abdominal muscles are associated with both spinal flexion and stabilization (Gardner-Morse and Stokes, 1998; Stokes *et al.*, 2011). Conversely, Quint *et al.*, (1998), found that despite the action of the agonist and antagonist muscles to raise the whole stiffness in axial torque and lateral flexion, this may destabilize the segment in flexion. In addition to that, the trunk muscles are not entirely coordinated, so the stability does not appear to be maximized (Stokes and Gardner-Morse, 2001).

Lumbar compartment syndrome was first diagnosed as a cause of LBP in 1981 (Carr *et al.,* 1985). Afterwards, several case reports notified the presence of para-spinal compartment syndrome in individuals with unexplained persistent back pain for a long duration (Carr *et al.*, 1985; Kitajima *et al.*, 2002; Wik *et al.*, 2010). Meanwhile, physiological and anatomical research measured the intramuscular pressure of the lumbar para-spinal muscles to highlight more information about aetiology of the LBP (Konno *et al.*, 1994). According to Wik *et al.*, (2010). The lumbar compartment syndrome is: ‘‘a rare condition defined as increased pressure within a closed fibro-osseous space, resulting in reduced blood flow and tissue perfusion in that space. The reduced perfusion causes ischemic pain and irreversible damage to the tissues of the compartment if unrecognized or left untreated’’. Thus it can be a potential cause of chronic LBP (Kobayashi *et al.*, 2010).

1.4.1 The erector spinae muscle

Many studies considered the lumbar erector spinae muscle to be composed of two muscles: a costal muscle known as iliocostalis lumborum, and a vertebral part known as longissimus thoracis. Both muscles have distinctive thoracic and lumbar parts (Bustami, 1986; Kalimo *et al.*, 1989; Daggfeldt *et al.*, 2000). The current study will be restricted to the fleshy longissimus thoracis and iliocostalis lumborum components of the erector spinae. The spinalis thoracis (dorsi) will not be included in the present study, because it is entirely aponeurotic in the lumbar region (Bierry *et al.*, 2008).

The thoracic parts consist of discrete muscle bundles which are segmentally attached to the lower thoracic spines and ribs. The lumbar part is the extended caudal tendons of the erector spinae aponeurosis (Benzel, 1997). The iliocostalis lumborum muscle (costal part) is the small fleshy bundles which originate from the superficial surface and the lateral margin of the erector spinae aponeurosis. In addition it is originated also from the lateral aspect of the posterior superior iliac spine (Bustami, 1986). It is inserted by a slim flat tendon into the tips of the transverse processes of the L1-4 and the lower ten ribs, while the longissimus muscle (vertebral part) arises by the larger fleshy fascicles from the deep surface of the erector spinae aponeurosis as well as the medial aspect of the posterior superior iliac spine. It is inserted through a musculotendinous fibre mainly into the accessory process and the proximal parts of the transverse processes of the upper four lumbar and lower eight thoracic vertebrae (Figure 1.4). Despite this, classification was agreed by some studies, however there are still some misconceptions about the nomenclature of the vertebral part of the muscle. Some researchers name the vertebral part as lumbar longissimus, while others call it the longissimus thoracic (Bustami, 1986). This study will refer to the muscle just as longissimus and this will be used throughout the study. An anterior septal reflection from the erector spinae aponeurosis is known as the lumbar intermuscular aponeurosis. This sagittal reflection separates between the iliocostalis lumborum and longissimus muscle, creating a compartment-like space (Brizzi and Todescan, 1983; Daggfeldt *et al.*, 2000).

Image data from human cadavers and software analysis of the physiologic cross-sectional areas of the lumbar erector spinae muscle fascicles support the classification of the lateral fascicles of the erector spinae muscle as part of the iliocostalis lumborum muscle (Daggfeldt *et al.*, 2000). Moreover, in both men and women, a large part of the iliocostalis lumborum origin is attached to the erector spinae aponeurosis. This implies the significant importance of the iliocostalis lumborum muscle in force transmission in the lumbar region. This study will adopt a classification of the lateral fascicles of the lumbar part of the lumbar erector spinae as part of iliocostalis lumborum (Daggfeldt *et al.*, 2000). In both male and female, a large part of the erector spinae fibres of lumbar origin attached to the erector spinae aponeurosis (Daggfeldt *et al.*, 2000). These results are of importance for biomechanical analysis of force transmission in the lumbar spine.

The superficial part of the erector spinae, the iliocostalis lumborum muscle, is attached by strap tendons into the tips of the transverse processes of the L1-4 and the lower ten ribs (Bustami, 1986). While, the deep part longissimus muscle is inserted through a musculotendinous fibre mainly into the accessory process and into the proximal ends of the transverse processes of the L1-4 and lower eight thoracic vertebrae (Bustami, 1986; Macintosh and Bogduk, 1987). The sort of attachments of the iliocostalis lumborum and the longissimus muscles were insufficiently described in the literature. The existence of the two parts of the erector spinae muscles separated by the inter-muscular aponeurosis, are of substantial importance in biomechanical analyses of the lumbar para-spinal compartment. This anatomical relationship should be put in consideration when dealing with an individual with LBP.

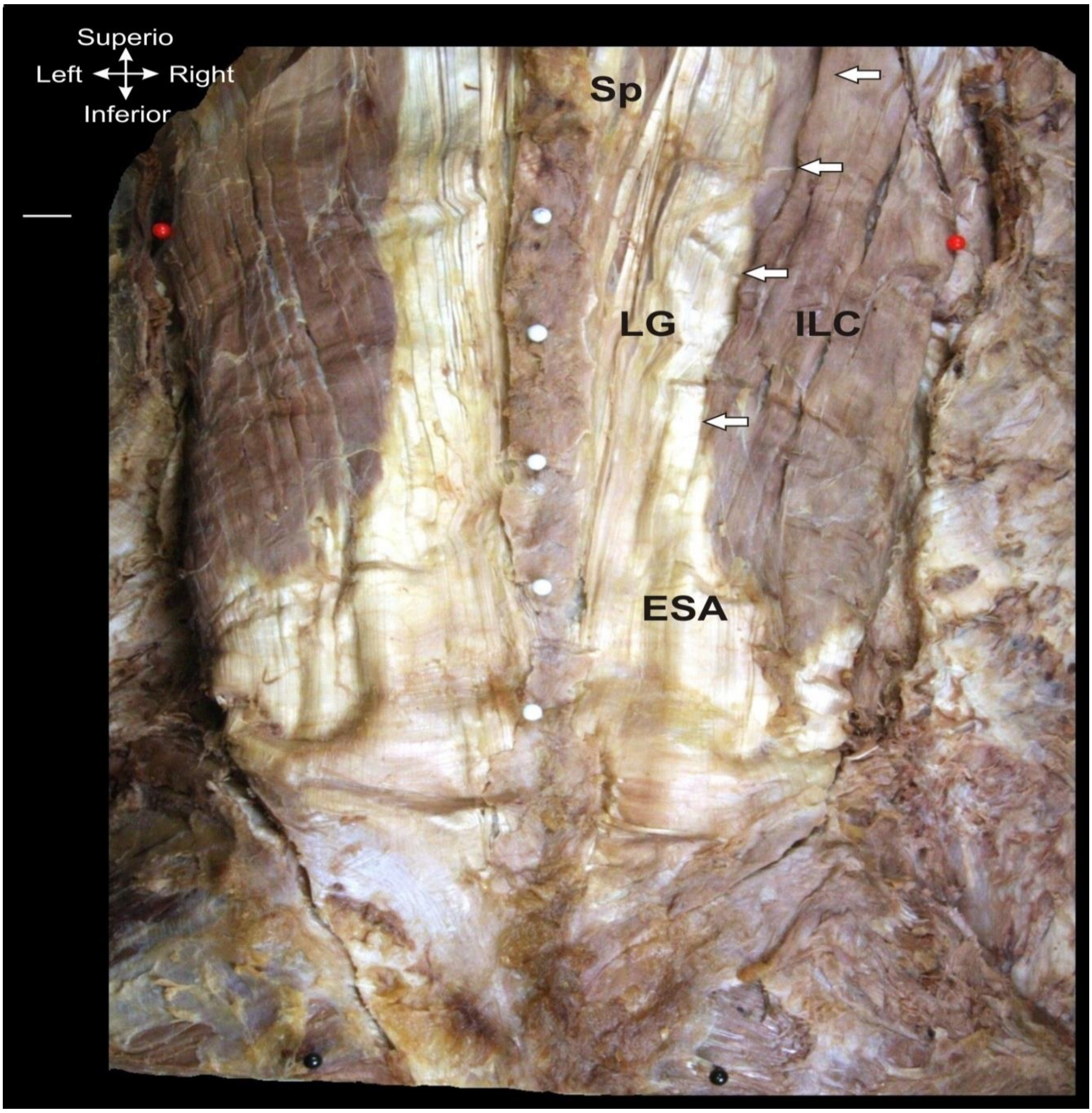

Figure 1.4 Posterior view of the lumbar region illustrates the muscles of the lumbar portion of the erector spinae muscle: iliocostalis muscle (ILC), longissimus (LG) and Spinalis (Sp). The cleft between the iliocostalis lumborum muscle and the longissimus muscle was noted in all specimens. The iliocostalis lumborum and the longissimus muscles fused distally with the aponeurosis of the erector spinae muscle. Scale bar = 1 cm.

1.4.2 The lumbar multifidus muscle

The anatomical description of the lumbar MF muscle has been illustrated in anatomy textbooks and articles because of its important mechanical functions for the lumbar spine in terms of mobility and stability. However, only the basic function of these muscles has been explained and without giving precise details of their attachments (Mattila *et al.*, 1986; Hides *et al.*, 1996). The lumbar MF muscle is one of the most important primary back muscles and the largest muscle that directly spans the lumbosacral junction (Zhu *et al.*, 1989; Lonnemann *et al.*, 2008).

It is the most medial para-spinal muscle covering the lumbar facet joints and lateral to the spinous processes. Thus, it occupies the groove between the spinous process and transverse process and is well developed in the lumbar region (Lonnemann *et al.*, 2008; Watson *et al.*, 2008). Trials to explain the basic function of the MF muscle as an important element in spine motion have enthused investigations of the muscle in the fields of physiology, histology, biomechanics, gross morphology, and imaging. A detailed anatomical description of the MF muscle is essential for biomechanical study, physiotherapy, and electromyography (EMG) evaluation of the lumbar spine. Also the MF muscle dysfunction has been found to be associated with LPB or other degenerative disc diseases (Mattila *et al.*, 1986; Hides *et al.*, 1996).

Previous studies have focused on the role of the para-spinal muscles on the aetiology and management of patients with chronic LPB. Findings of these studies derived from imaging studies concluding the atrophy of the MF muscle in such patients as compared with asymptomatic healthy control patients. However, there are discrepancies between these results; some claim a significant decrease in the para-spinal muscles size between the symptomatic patients and the control patients, whereas, others reveal no difference between the two groups (Masuda *et al.*, 2005; Hides *et al.*, 2008b).

A study aimed to locate the cleft between the MF and longissimus muscles in 30 cadavers. The existence of a natural cleavage plane between these muscles was clearly identified in all specimens. The cleavage was structurally separated by the intermuscular septum in 91.7% of cases. The mean distance between the level of the cleavage plane and the midline was 4 cm at the level of the L4 spinous process (Vialle *et al.*, 2005). The combined effect of MF muscle atrophy and compressed anterior disc height could be the cause of lumbar degenerative spondylolisthesis. Nevertheless, the erector spinae muscle hypertrophy could be a mechanism to compensate for this instability (Wang *et al.*, 2014).

No difference in the MF architecture has been observed between the sides, but there is considerable individual variation in the bulk of the muscle. In addition the fascicles of male cadavers had approximately 25% larger cross sectional area than in the female cadavers. This difference in size may have been due to a skeletal adaptation as women generally have a wider pelvis than men (Lonnemann *et al.*, 2008). Furthermore, in patients with chronic LBP, asymmetry between sides could be seen as a presenting feature of a unilateral pain distribution (Hides *et al.*, 2008b).

The lumbar MF is a key muscle which contributes to lumbar stability. Three organised regions were identified: superficial, intermediate and deep. Nonetheless, the intermediate MF was absent at L5. The bulk and the size of the muscle fibres were reduced from superficial to deep. This multilayer differential appears to be important for specific tasks and/or to maintain stability (Rosatelli *et al.*, 2008). It was noted that MF acts optimally at upright standing in the normal individual, while maximum contraction of the muscle occurs at 25° forward flexion in patients with LBP. Moreover, this role of the MF could be modified in chronic LBP patients to achieve the lumbar stability. Assessment of the change in muscle size in reaction to different postures is found to be helpful (Lee *et al.*, 2006c).

The lumbar MF consists of five myotomes therefore, and the muscle is innervated uni-segmentally, each supplied by a nerve of that segment. (Macintosh *et al.*, 1986). The central nervous system recruits MF and the anterolateral abdominal muscles to stabilize the spine (Hodges and Richardson, 1997a). There is a primary reflex between the mechanoreceptors in the supra-spinous ligament and in the MF muscle. The activity of the MF muscle can be triggered by any stress or load on the ligament. This activation of the MF muscle can be critical at levels (45-50% of body weight) and can be harmful for the tissue (Solomonow *et al.*, 1998). Moreover, the superficial MF plays a role in the control of spine orientation, while the deep MF fibres help to control the intersegmental motion (Moseley *et al.*, 2002). Surprisingly, even among very active athletes with LBP, there is muscle atrophy and poor MF muscle contraction, but specific exercises can promote a substantial increase in the cross surface area with relief of the pain (Hides *et al.*, 2008b, 2011).

Recently, physiotherapists have focussed most of their attention in the MF muscle. They claim that there is a significant decrease in the cross-sectional area of the MF muscle in the affected low back side. Furthermore, this atrophy of the MF muscle and psoas muscle has been designed for spinal stability exercises (Barker *et. al.*, 2004a; Hides *et al.*, 2007) focused on the disuse atrophy (bed rest) and the resultant change in lumbar musculoskeletal function. The cross-sectional area of the MF muscle was measured by MRI and was decreased by day fourteen of bed rest (P = 0.04). It was concluded that bed rest led to specific atrophy of the MF muscle. This evidence may reflect some of the changes which are seen in patients with LBP. Although possessing high degree of fitness, athletes still have LBP. The MF muscle showed an increase in the cross-sectional area at the L5 in players with LBP. This increase was due to a compensatory hypertrophy of the MF muscle similar to that in trainees without LBP. Consequently the level of pain was less among the players with LBP. Surprisingly, the MF muscle atrophy can even be evident in healthy active athletes who suffer from LBP (Hides *et. al.*, 2008b).

The various descriptions of MF muscle morphology and its role in lumbar spinal stability, raise the need of this study to prove the various previous documentations of MF muscle morphology. Histological evidence will validate gross observational data and provide information of value for future biomechanical and electromyography studies.

1.4.3 The lumbar inter-spinalis muscles

These are four pairs of short deep muscles that intervene in the four lumbar interspinous spaces. The inter-spinalis muscles are small, thin, quadrangular muscles that bridge the lumbar interspinous spaces along either sides of the inter-spinous ligament. Thus, they attach the spinous processes between the sub-adjacent lumbar vertebrae. Because of their small size and short fibres, the inter-spinalis muscles would not contribute considerably in sagittal rotation of the vertebrae above as their positions are assumed (Board *et al.*, 2006). Nevertheless, these small muscles may have a proprioceptive role (Gilchrist *et al.*, 2003).

MRI studies documented the associated degenerative inter- inter-spinalis muscles injury with interspinous ligamentous rupture. It is very important this combined injury is not missed when it is the only finding recognized on MRI of the lumbosacral spine of a patient with LBP (Jinkins, 2002). These muscles were poorly documented, and further knowledge needs to be added. The current practical evaluation of the inter-spinous ligaments needs to be reassessed and may thereby improve future training concepts.

1.4.4 The transversus abdominis muscle

The human vertebral column is an unstable structure and, hence, it is necessary for equilibrium and balance to be provided by the surrounding para-spinal "core" muscles. Most importantly, the transversus abdominis muscle is considered as the major anterior contributor to spinal stability. Concurrently, several other muscles are now assumed to participate in stabilizing the spine. The actions of these muscles are quite flexible, synergistic and could be modified to fit each variable task (Hodges *et al.,* 1997c; Sapsford *et al.,* 2001). Secondly, Barker *et al.* (2004b) argued that the transversus abdominis muscle could influence the control of the segmental motion, most likely through the lumbar fascia. Interestingly, the postural responses of the transversus abdominis muscle were also found to differ between body positions, with recruitment delayed in sitting compared to standing (Urquhart *et al.,* 2005a; 2005b). Normally, thickness of the transversus abdominis muscle is symmetrical bilaterally either during rest or whilst contracted, while asymmetry is detected in the lateral abdominal muscles only in patients with LBP (Springer *et al.,* 2006). However, a small area of attachment between the abdominal musculature and the TLF exists (Macintosh *et. al.,* 1987), so it cannot generate a significant tension in the TLF. Biomechanical studies revealed that the anti-flexion moment generated in this way is therefore of limited value (Barker *et al.*, 2006; Thomas., 2006; Izzo *et al.*, 2007).

Hodges *et al.*, (2005) spotlighted the positive correlation between the elevated intra-abdominal pressure and the increased stiffness of the lumbar spine, specifically at L2 and L4 levels. Different degrees of intensity of abdominal bracing are required to achieve the different movements and exercises when just spinal stability is required (McGill *et al.*, 2009a; 2009b). In contrast, Ivancic *et al.*, (2002) recommended that the abdominal belt be used to contribute only to passive spinal stability. The trunk muscles have capacity for both isometric contraction for stability and rhythmic contraction for ventilation. Thus it is observed that the inspiration concurred with increases in spinal stability, while there is less stability during expiration (Lee and Kang, 2002; Wang and McGill, 2008).

There is scant information that acknowledged the useful effects of the belts on spinal stability. Thus, it cannot be confirmed that the abdominal belts will give more support to the lumbar spines during load lifting (Minor, 1996; Miyamoto *et al.*, 1999). In addition, a successful decrease in trunk instability in all three planes was obtained from only the elastic belt (Granata *et al.*, 1997). Evidence suggests that a personal lift assist device can support lumbar spinal stability alone or in combination with elevated intra-abdominal pressure (Abdoli *et al.*, 2006). However, the usefulness of these abdominal belts should be understood as risk avoidance from the perspective of restricting the activation of some lumbar extensor muscles (Cholewicki *et al.*, 1999). Hence, contradictory suggestions appear regarding the effectiveness of wearing abdominal belts by labourers (Giorcelli *et al.*, 2001).

It was thought that the commercial abdominal belts on the market which were used by different people and workers could support lumbar stability from excessive load and/or increased intra-abdominal pressure. Physiological parameters were measured among weight-lifting elites such as intra-abdominal pressure and muscles activity. Different loads have been applied with and without wearing belts. There was decrease in the erector spinae muscle activity with the breath held, suggesting a reduced load on the lumbar spine, although wearing a belt did not augment this reduction. However, the muscle activity and the intra-abdominal pressure for short duration lifting tasks, does not give an answer about the effectiveness of wearing abdominal belts by labourers (Mcgill *et al.*, 1990b). Further, evidence suggests that both wearing an abdominal belt and elevated intra-abdominal pressure can, separately or together, increase the stability of the lumbar spine. However, the decreased activation of some extensor muscles should be borne in mind when considering the usefulness of the abdominal belt (Cholewicki *et al.*, 1999). Moreover, the abdominal belt only contributed to the passive stability of the lumbar spine without enhancing the active stability of the lumbar extensor muscles (Ivancic *et al.*, 2002).

Despite the aforementioned evidence, there looks to be no underlying mechanical principle for using the transversus abdominis muscle to augment lumbar stability. Rather, the transversus abdominis muscle, in association with other muscles, may create a bracing effect that enhances spinal stability (Grenier and McGill, 2007).

Multi-planar segmental lumbar motion can be achieved by the MF muscle, quadratus lumborum, transversus abdominis, oblique abdominis and psoas major muscles as they are enclosing the lumbar segments posteriorly from the spinous process to the anterolateral aspects of the vertebral body bilaterally (Jemmett *et al.*, 2004; Karst and Willett 2004). Furthermore, no single muscle dominated in the supporting of spinal stability, and their roles were task-dependant (Kavcic *et al.*, 2004). However, these intervertebral motions were significantly restricted in patients due to persistent muscle activation as a protective mechanism by which the neuromuscular system prevents further damage to the diseased spinal segment (Kaigle *et al.*, 1998; Herrmann *et al.*, 2006; Lamoth *et al.*, 2006). It was proposed that these motor control changes are functional, in that they enhance spinal stability (van Dieën *et al.*, 2003a).

1.4.5 The cross sectional area

The combined physiologic cross-sectional area of the erector spinae muscle was 11.6 cm^2, (Delp *et al.*, 2001). The ImageJ software (Rasband, 1997-2014) method was highly reliable and reproducible to measure the cross-sectional area of the para-spinal muscles (Fortin and Battie, 2012). Para-spinal muscle asymmetry greater than 10% was commonly found in men without a history of LBP. This suggested that a mild degree of asymmetry is acceptable and it is not an indication of any spinal pathology; thus asymmetry in LBP patients may be misleading (Niemelainen *et al.*, 2011).

The cross-sectional area and composition of the para-spinal muscles have been associated with LBP. However, considerable MF muscle asymmetry has also been reported in men who were asymptomatic, and little is known about other factors such as handedness which can affect the para-spinal muscle asymmetry (Chaput *et al.*, 2013). The cross-sectional area of the MF muscle at L5-S1, was affected by handedness only, whereas the thickness of the erector spinae muscle was affected by age and handedness and was asymmetrical at L3-L4 (Chaput *et al.*, 2013).

There is longstanding controversy and debate regarding para-spinal muscles morphology as a predictor of LBP. A longitudinal study stated that the variation of muscle thickness carries a limited prediction value of LBP in men (Fortin *et al.*, 2014). Regular MRI indicated a significant reduction in the cross-sectional area of the MF muscle over two weeks of bed rest. Nevertheless, this reduction in the thickness was reversible after four days of resuming normal daily activities. The selective negative effects of bed rest can be superimposed over the pain in already immobile patients due to severe LBP (Hides *et al.*, 2007). It was also found that LBP in ballet dancers was associated with a unilaterally decreased cross-sectional area of the MF muscle, but not in other para-vertebral muscles (Gildea *et al.,* 2013).

Body positions can affect the physiological status of the para-spinal muscles. The erector spinae muscle's thickness and blood supply were increased during relaxed extension and decreased during relaxed flexion, in ultrasonography of asymptomatic subjects (Masuda *et al.*, 2005). The fatty infiltration within the MF muscle is significantly higher in individuals with chronic LBP than in asymptomatic volunteers (Mengiardi *et al.*, 2006). A combination of genetic and environmental factors may affect the cross-sectional area of the para-spinal muscles, rather than anthropometric factors and lifestyle choices in adulthood (Gibbons *et al.*, 1998). Also, the deposition of fat in the lumbar MF and erector spinae muscles was noted in sway-back posture individuals as compared to the control group. Pain may be the cause of the difference in the amount of fat observed in the groups with the same postural deviation. This finding suggested that any individual with sway-back posture may be susceptible to histological changes in their lumbar MF and erector spinae muscles due to the persistent pain and their abnormal posture (Pezolato *et al.*, 2012).

1.4.6 Muscle fibre angles

Surface EMG recording depends on a detailed awareness of the regional anatomy of the area required to be tested. This implies exact knowledge of the orientation of the muscle fibres of the erector spinae and MF muscles. It is regrettable that anatomical textbooks and atlases describe only the attachments of a muscle, without giving more precise details about muscle fibre direction (Macintosh and Bogduk, 1991). Thus, this information about the muscle fibre direction can enhance current understanding of the functionality of the human para-spinal muscles and so improve future training concepts (Stark *et al.*, 2013). The landmark derived reference lines were very reliable and reproducible in detection of the direction of muscle fibres at L2-L3 for the iliocostalis lumborum muscle and at L4-L5 for the MF muscle (Biedermann *et al.*, 1991)

There is no difference in accuracy in detecting the fibre direction of the MF muscle between men and women (Biedermann *et al.*, 1991). Considerable individual dissimilarities in the fibre orientation of the iliocostalis lumborum, the longissimus and MF muscles were detected, so it brings criticism into the validity of the application of a two fixed-angle grid system. The angulation of the fibres of the MF and iliocostalis lumborum were determined without difficulty in application by the use of three surface anatomical points, while no dependable index was agreed for the longissimus muscle (De Foa *et al.*, 1989).

1.5 The lumbar muscle attachments

The location and type of attachment of the lumbar para-vertebral muscles influence not only vertebral movement, but also stability. The extensor muscles of the lumbar vertebrae provide a great degree of spinal stability and play an important role in controlling motion (Thorstensson and Carlson, 1987; Hansen *et al.*, 2006; Ward *et al.*, 2009; Cornwall *et al.*, 2011). The location and tissue constitution of the attachment of the longissimus, inter-spinalis, iliocostalis lumborum and MF muscles have been disputed (Gracovetsky *et al.*, 1985; Hodges and Richardson, 1997b; Hides *et al.*, 2008b; Rosatelli *et al.*, 2008). Particularly, the variability of the iliocostalis lumborum attachment to the transversus process will be investigated histologically. Therefore, this study aims to quantify the attachment of these muscles and to describe their tissue constitution histologically.

1.5.1 Entheses

Enthesis has been defined as the site of attachment of a tendon, ligament or joint capsule to the bony skeleton via a functionally graded, multi-tissue of spatial gradients in structure and mechanical properties (Benjamin and McGonagle, 2009; Schwartz *et al.*, 2012; Lu and Thomopoulos, 2013). Generally tendons connect muscles to bones, and thus transmit muscular force and apply it to the bone, however the tendon itself may be subjected to shear and compression when it passes over bony margins or through a fibrous pulley (Benjamin *et al.*, 2008; Liu *et al.*, 2011). Tendons or ligaments continue with the bone by a multi-tissue interface with spatial gradients in structure and biomechanical properties. These multi-tissue gradients are essential to reduce stress application and intermediate load handover between soft tissues and hard tissues (Moriggl *et al.*, 2003; Lu and Thomopoulos, 2013). In addition, a mineral gradient is also thought to play a vital role for minimizing stress focus at mature fibrocartilaginous-bony interfaces (Schwartz *et al.*, 2012; Spalazzi *et al.*, 2013). The importance of the enthesis fibrocartilage has taken more attention recently. The enthesis is a structure in which the fibrocartilage prevents direct cellular contact between osteocytes and tendon or ligament cells. Thus it acts as a mechanical barrier that prevents blood and fluid diffusion from bone to tendon (Benjamin and Mcgonagle, 2009).

Many studies have agreed to classify the histological structure of the tendons or ligament into two main kinds of attachment sites between these soft tissues and bones: fibrous (indirect) and fibrocartilaginous (direct) according to their structure (Benjamin *et al.*, 1995; Benjamin and McGonagle 2001; Benjamin and Ralphs, 2001; Spalazzi *et al.*, 2013). The term ‘direct’ is used in the absence of a periosteum at fibrocartilaginous entheses and hence a ‘direct’ attachment of the tendon or ligament to the bone exists, while with ‘indirect’ fibrous entheses, the tendon or ligament connects indirectly to the bone by means of periosteum.

Fibrocartilaginous entheses, as their name suggests, are structures where chondrogenesis has occurred. Hence, four zones of tissue are commonly present: pure dense fibrous connective tissue, uncalcified fibrocartilage, calcified fibrocartilage, and bone. The lack of a clear delineation and the minute size of these zones which define two fibrocartilaginous entheses, may be the major reason for the entheses being relatively less well described (Benjamin *et al.*, 2006). A more detailed classification has been adopted (Hems and Tillmann, 2000), including a distinction between periosteal, bony and fibrocartilaginous attachments. Overall, the fibrous zone in any classification is located in the most superficial or distal part of the entheses from the bone (Benjamin *et al.*, 2006). The calcified fibrocartilage fixes the tendon to the bone and generates a diffusion barrier between the two, while the uncalcified fibrocartilage decreases collagen fibre bending and tendon narrowing away from the tidemark. The additional fibrocartilaginous differentiations in the tendon and/or bone next to the enthesial site, is known as an "enthesis organ" which is important in reducing wear and tear of the enthesis (Benjamin *et al.*, 2002).

It has been suggested that the fibrocartilage plays a specific role at entheses in preventing collagen fibres from bending at the bony interface. Thus, it is expected that the more 'mobile' tendons have more fibrocartilaginous elements (Frowen and Benjamin, 1995). The bone at the site of an enthesis may be subjected to avulsion fractures and commonly occurring enthesopathies such as tennis elbow, despite so little attention being paid to entheses regionally (Benjamin and McGonagle, 2001). Specifically, the fibrous entheses, has been paid very little attention compared to the fibrocartilaginous type, despite fibrous entheses being associated with some of the largest and most forceful muscles such as deltoid (Benjamin *et al.*, 2002).

It was suggested that the mineral gradient in the enthesis could play an important role for indulgence of stress applications at mature fibrocartilaginous interfaces (Schwartz *et al.*, 2012). It is usual in clinical practise to get failure of the surgical repair of injured tendon to bone, assuming that the enthesis does not regenerate in the healing setting. A study was done on the development of murine supraspinatus tendon enthesis. Then an ultra-structural scale of mineral growth across the developing enthesis was studied by CT scan and transmission electron microscopy. Measurements have indicated constant increases in bone apatite mineral density with time, while the mineral-to-collagen ratio remained constant. This may be of clinical importance for the growth and mechanical stability of the tendon-to-bone attachment throughout the healing process of a repaired tendon (Schwartz *et al.*, 2012).

Regarding the known high occurrence of tendon and ligament ruptures, interface restoration stands as a significant clinical challenge as there is no perfect process for their repair (Lu and Thomopoulos, 2013). It is a big challenge to surgical repair and tissue engineering to find an effective solution to this problem at the attachment of soft tendon to hard tissue (Thomopoulos *et al.*, 2010). The enthesis gradients are not redeveloped during tendon-to-bone healing, leading to a high incidence of failure after surgical repair. The structural composition and biomechanical properties of the enthesis should be put in consideration prior to any repair approach. Mechanical training is also necessary for the development of the enthesis (Thomopoulos *et al.*, 2010).

A thorough understanding of enthesis development may allow tissue engineers to develop cures that regenerate the natural tendon-to-bone insertion. Any successful tendon repair trials should be cell-based repair therapies which need an understanding of the normal development of tendon tissues, including their differentiated zones of the fibrocartilaginous insertion site and at the musculotendinous junction (Liu *et al.*, 2011). Furthermore, genetic engineers attempt to regenerate a functional tissue in *in vitro* culture. However, a lack of knowledge of normal tendon development has led to the suppression of these efforts. Therefore, a better understanding of the structural and ultra-structural nature and composition of tendon development and their regional variability will be essential background knowledge for any repair process. The paucity of the information regarding tendon enthesis, particularly for the lumbar muscles attachment, necessitates this study investigation of the histological nature of the iliocostalis lumborum, longissimus and MF muscle tendons entheses.

1.5.2 Histological structure of the muscles attachment

The microscopic structure of the myotendineal junction in rat Achilles tendons was investigated. The slow-twitch muscle fibres (type 1) and fast-twitch (type 2) muscle fibres were detected at the myotendinous junction. (Jozsa *et al.*, 1991b). A similar study was done to investigate the macromolecular composition of the same junction. Chondroitin and heparin sulphate were detected also, while the detection of hyaluronic acid was also questionable, but the type of collagenous component found in the myotendinous junction was type I collagen with a small quantity of type III collagen. The high concentration of the polysaccharides may enhance the adhesion capacity between the muscle cell membrane and tendineal collagen fibrils. Jarvinen (*et al.*, 1991) concluded that the myotendinous junction was well differentiated histochemically and immunohistochemically.

The three-dimensional structure of human tendons was also investigated. Both the epitenon and peritenon are composed of a dense network of variable orientation which form a spiral structure of the collagen fibrils crossing the tendon fibres. These fibril bundles are held together by endotenon. In the myotendinous junction they have the same arrangement in the rat model. This complex structure of human tendons perhaps provides a good absorbent buffer system to different directional forces during movement and activity (Jozsa *et al.*, 1991a).

1.6 Aim of the study

The aforementioned literature and background data demonstrate the need for a detailed quantitative model of these anatomical structures. This understanding will be fundamental for better evaluation of the role of each structure. A detailed anatomical knowledge will enable more precise testing and understanding of normal back function, and its failure in a variety of common disorders. These outcomes could re-emphasise current concepts regarding core stability and LBP among medical, sport and physiotherapy practices.

This study aims to investigate the surface area, curvature and the angle of orientation of the lumbar FJ. This will be done by three-dimensional study. The orientation of the lumbar facets will be documented and its relation to degenerative diseases of the lumbar spines will be discussed. This three-dimensional approach will test the hypothesis that the lower lumbar AFs are more coronal and have a larger surface area than those in the upper lumbar vertebrae. The second hypothesis that needs to be tested is that change in facet orientation is related to FJ degeneration.

There is a paucity of information regarding interactions between these superficial myofascial tissues which contribute to stability of the lumbar vertebral column. The mentioned literature and background data demonstrate the need for detailed documentation of these myofascial connections. The current study aims to: (i) document the layers of the TLF and the myofascial connections between the TLF and the surrounding superficial muscles such as the latissimus dorsi, transversus abdominis and gluteus maximus muscles. The project seeks to identify tissue connections of potential mechanical importance; (ii) test the hypothesis that a single continuous fascia (described as para-spinal retinacular sheath) encloses the para-spinal muscles from the spinous process to the transverse process; (iii) test the hypothesis that a lateral inter-fascial triangle and raphe exist at the connection between the transversus abdominis, internal oblique and the latissimus dorsi muscles with the TLF. This understanding will be fundamental to explaining the normal mechanism of spinal stability, and its failure may cause a variety of common back disorders. These outcomes could re-emphasise current concepts regarding core stability among medical, sport and physiotherapy practices. Eventually, this will better inform training and rehabilitation protocols for recovery and prevention of the LBP.

The lumbar intermuscular clefts are of clinical importance in surgical approaches to the lumbar spines. The morphology and function of the lumbar extensor muscles will be investigated. The study will primarily prove the existence of an intermuscular cleft between the MF and erector spinae muscles. The surface landmarks data for the MF and iliocostalis lumborum muscles are essential for recoding muscle activities by electromyography. This study will reference the fibre direction of these muscles to the lumbar surface anatomy. The morphological measurements of the lumbar MF, longissimus and iliocostalis lumborum muscles will be investigated. Of particular importance, the cross sectional area of the MF muscle will be analysed. The foot prints of the MF, longissimus, iliocostalis lumborum and the lumbar inter-spinalis muscles will allow measurement of the surface areas of the attachments of these muscles.

This study aims to quantify the histologic nature of the para-vertebral muscle attachment to the lumbar vertebrae and to categorise the types of the entheses at these attachment sites. In order to decrease the subjectivity of dissection-based investigations, the study examines the histological structure at the site of soft tissue-bone interface. This may assist in discrimination between tendon and other soft tissue such as joint capsule.

Chapter 2

Materials and Methods

2.1 Three dimensional modelling of the lumbar facets

2.1.1 Specimens

Fifty six sets of articulated dry lumbar vertebrae were collected from the Laboratory of Human Anatomy, Thomson Building of the University of Glasgow. No age or sex data were available for this collection. Six sets of the lumbar vertebrae were excluded from the study because some vertebrae were missing from the sets or had gross damage.

2.1.2 Gross observation

All sets were inspected thoroughly and carefully to document any gross deformities or degenerative features such as thickened margins of the vertebral body and the articular facets, bony growth likes osteophyte and compression or shortening of the vertebral body. Each vertebra was carefully and thoroughly inspected to ensure that each set of the lumbar vertebrae belonged to the same donor and in the correct articulated sequence. It was best inspected from top view in order to observe variation of the articular facet shape. The photos were taken by the Canon camera (EOS, 40D; Appendix V) for descriptive purpose. The shape has been categorised into three varieties: curved or C-shape, J-shape and flat shape (Figure 2.1).

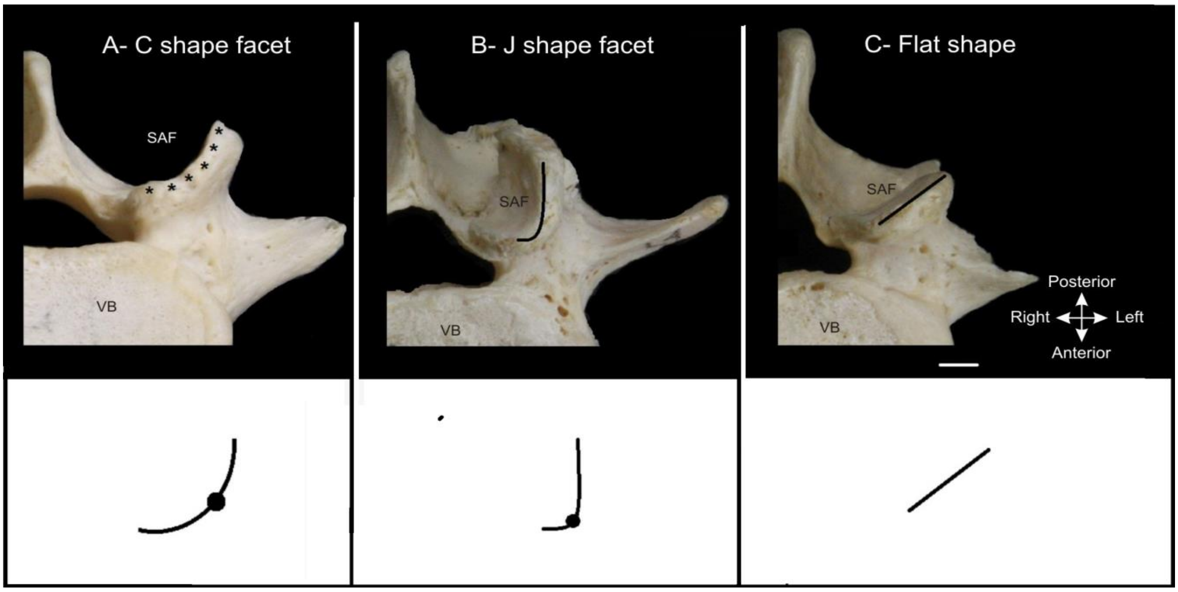

Figure 2.1 The classification of the shape of the facet curvature is defined as follows: C shape facet defined by an equidistant centre or apex and both sides are concave. J shape facet has the apex of curvature anteriorly with a concave anterior limb and straight posterior limb. While the flat or plane facet has no specific centre. Scale bar = 1cm.

2.1.3 Three-dimensional modelling of the articular facet

The articular facets were reconstructed into a virtual space using Microscribe (Immersion, USA). Then the data were presented as a three–dimensional model by Rhinoceros X5 software (Robert McNeel and Associates, USA). The facet surface area and angulation were measured by Rhinoceros X5 software. This allowed calculation of the surface area in mm^2 and also measurement of the angle of facet orientation. A transverse line (RL) was reconstructed between the tips of the right and left transverse processes of each vertebra. This line represented the coronal plane. Similarly, the sagittal plane was determined from a line which connects four points (Figure 2.2).

The angles R° and L° are representing the right and left facets orientation respectively, were measured using Rhinoceros X5 software as follows: the anteromedial (AM) and the posterolateral (PL) margins of the facet were used to determine the articular facet angle. The line connecting the AM and the PM margins of the superior facet intersect with the coronal plane. Thus it creates R° and L° angles. These angles vary from 0°, which is more coronal, to 90°, which is more sagittal (Figure 2.3).

The modelling and measurements were repeated in order to exclude intra-observer and inter-observer errors and to decrease the subjectivity in presenting the data. Therefore, the reconstruction modelling process was repeated at a different time and then the paired t-test was applied to the collected data on both occasions to exclude any intra-observer errors during the modelling. The modelling was also repeated by another student and in the same way the paired t-test was applied again to rule out any inter-observer errors.

In data analysis the paired t-test was applied to compare the mean of the surface area and the orientation of the right and left articular facets. Also the t-test was used to compare the mentioned parameters between any two levels of the lumbar vertebrae, while, the ANOVA test was used to compare the mean of the surface area and orientation of the lumbar facets of all lumbar levels to find any significant difference between the five vertebral levels.

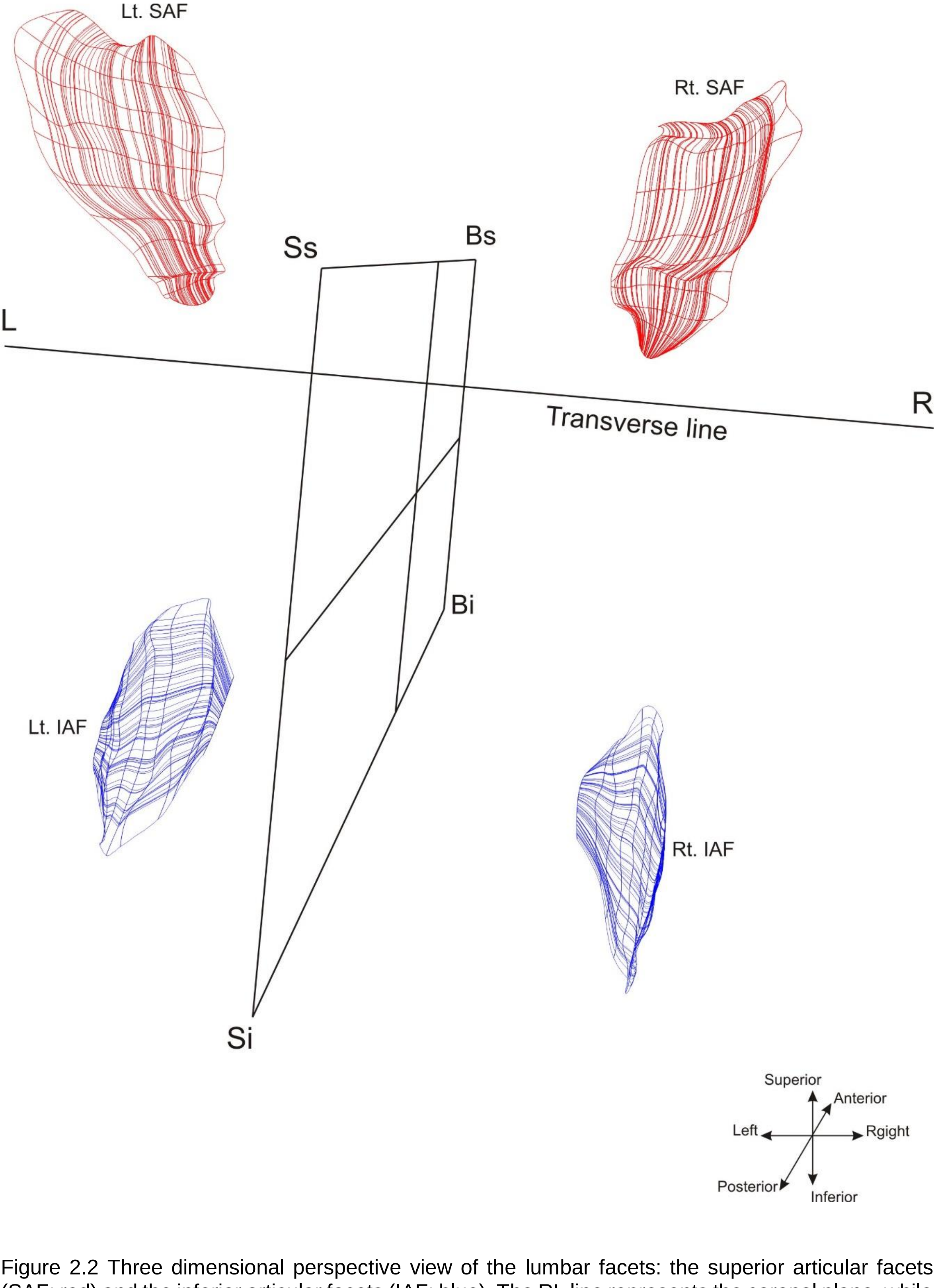

Figure 2.2 Three dimensional perspective view of the lumbar facets: the superior articular facets (SAF; red) and the inferior articular facets (IAF; blue). The RL line represents the coronal plane, while the sagittal plane is determined by four points: Ss is the superior mid-point of the tip of the spinous process, Bs is the mid-point on the posterior border of the superior surface of the vertebral body, Bi is the mid-point on the posterior border of the inferior surface of the vertebral body and finally Si is the inferior mid-point of the tip of the spinous process.

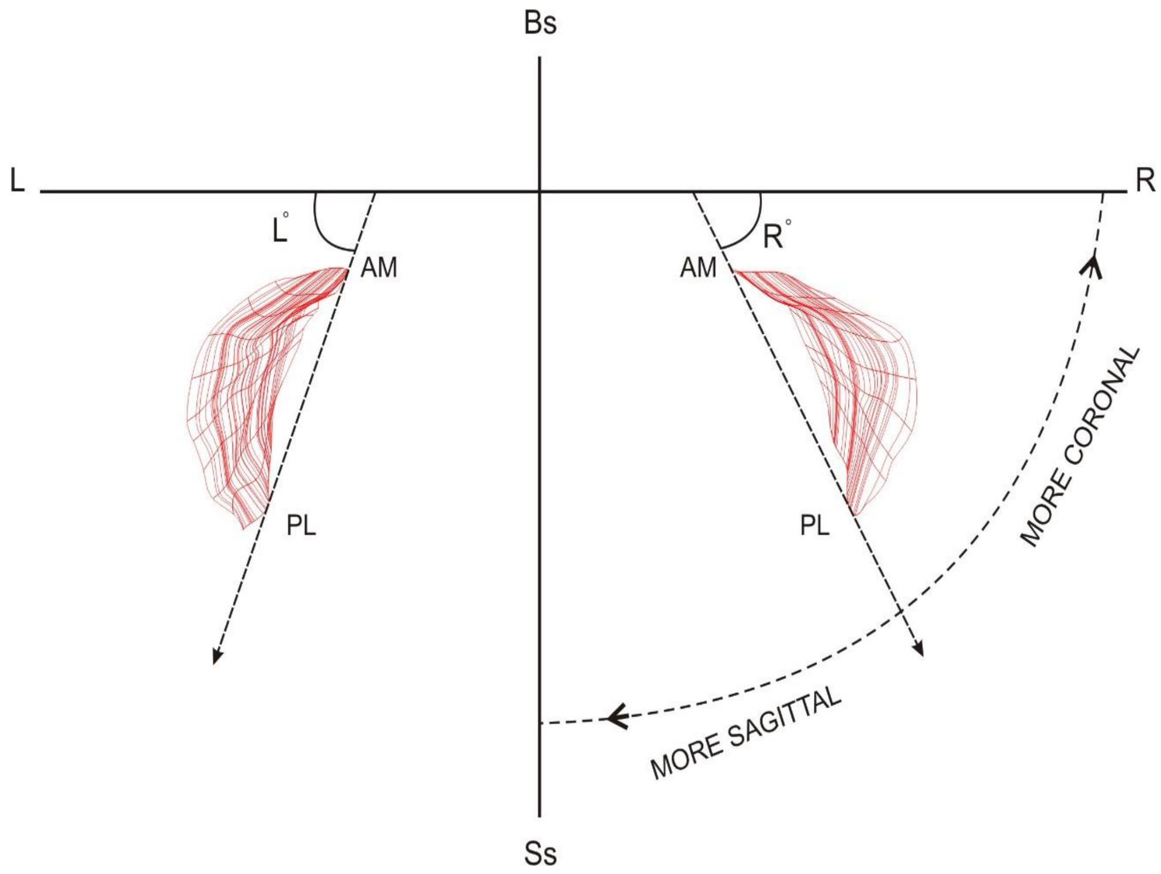

Figure 2.3 Three dimensional models of the superior lumbar superior facets. The reference planes were defined by the line (RL) between the tips of the right and left transverse processes (RL). The sagittal plane is detected by a line connecting the mid-point of the posterior border of the superior surface of the vertebral body (Bs) to the superior tip of the spinous process (Ss), while (AM) and (PL) were used to define the anteromedial and the posterolateral margins of the facets. The angles R° and L° were calculated by Rhinoceros X5 software.

2.2 The superficial myofascial interactions

2.2.1 Specimens

Twenty five human donors (twelve male, thirteen female; 80.7 ± 9.9 years; weight: 66.9 ± 14.7 kg; height: 166.7 ± 7.0 cm) were arbitrarily selected from the Laboratory of Human Anatomy, the University of Glasgow. Permission for use of the cadavers and specimens was granted by the lead anatomy license holder of the University under the terms of the Anatomy Act (1989) and the Human Tissue (Scotland, 2006) amendments. All donors were embalmed through the standard embalming process of the Laboratory of Human Anatomy, School of Life Sciences, the University of Glasgow (Appendix I).

All the specimens were dissected using standard surgical equipment and with the aid of six-time magnification surgical microscopes. High intensity lighting was used to ensure optimal visualisation of the specimens at all times. Following the removal of the skin, dissection was directed to the bilaminar posterior layer of the TLF. The superficial and deep lamina were studied using visual inspection and micro dissection. The gross deposition and features of the intact posterior layer of the TLF was inspected thoroughly. Manual traction has been applied to test the fascial continuity between regions.

2.2.2 Measuring fibre angles by ImageJ software

The twenty five specimens were photographed in prone extension position. The angle of the fibres of the superficial and deep laminae of the posterior layer of the TLF were measured by ImageJ software (Rasband, 1997-2014) as shown in figure 2.4. The region was lined into five levels, then the range of angle of the direction of the superficial and deep fibres of the posterior layer were measured by the ImageJ programme (Rasband, 1997-2014) for each level. The angle is defined by intersection of two lines. The first represents the direction of the fibre and the second line is the vertical line which is aligned best to fit the line of the vertebral spinous processes (Figure 2.5). Then these angles were converted to acute angles below the horizontal line according to convention. Photos have been taken by the Canon camera (EOS, 40D; Appendix V) for documentation purposes.

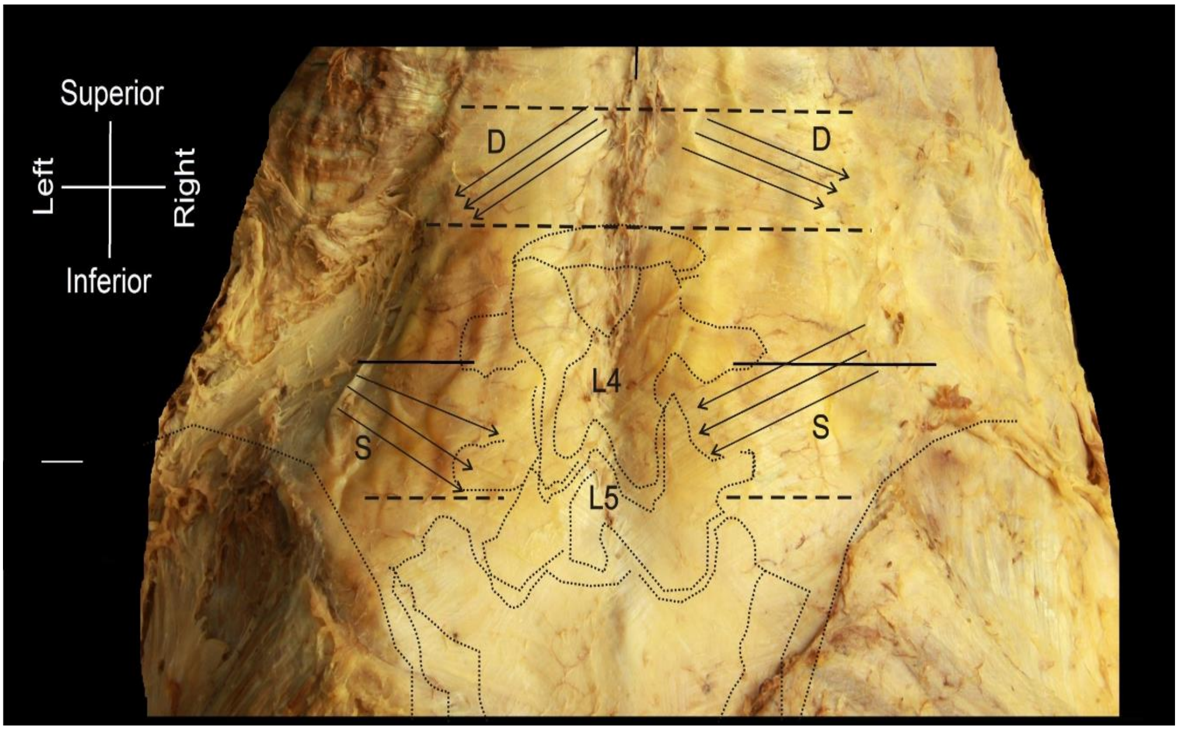

Figure 2.4 Schematic illustration over the TLF shows how the direction of the TLF fibre was measured. The levels of the lumbar spinous processes were marked by interrupted transverse line (Only L4 was not interrupted as a reference). The direction of the superficial and deep fibres are represented by (S) arrows and (D) arrows respectively. These directions, which are presented by arrow, are applied to each level. Scale bar = 1cm.

2.2.3 Measuring fibre angles by Rhinoceros software

Six of the specimens were fixed securely to a wooden board by drilling a number of pins. Then the Microscribe device (Appendix VII) was used to make a virtual three dimensional model of the fibres of the superficial lamina of the posterior layer. The pointer of the Microscribe was used very carefully to follow each fibre by a series of gentle touches. This allowed the measurement of the angle of the bundles of the posterior layer of the TLF.

Then each individual fibre of the superficial lamina of the posterior layer was resected methodically. This was done by careful handling of discrete bundles of the fibres with tiny forceps and bisecting them close to the midline. After that each bundle was peeled laterally until its continuation with the latissimus dorsi muscular fibres or its fusion with the middle layer of the TLF. The peeling process was done smoothly with only gentle traction. Dissection was inevitable only to separate the more distal parts of the superficial lamina from the deep lamina of the posterior layer of the TLF, especially from the level of L5 downward. The criteria for dissection was as follows: each muscle fibre or fascial bundle was identified first and followed until its attachment to a bone or its fusion with another muscle or fascia. The criteria also followed any fascicle which continued as a tendon or disappeared into indistinct connective tissue, while any diffused and/or disorganized tissues were not included. Thus, the dissection protocol was limited to retaining bands of connective tissue in which specific fascicles could be followed (including under magnification).

After exposing the whole possible part of the deep lamina of the posterior layer, the Microscribe was carefully applied again to initiate a virtual model of the deep fibres (Figure 2.5). Six of the specimens were reconstructed in virtual space by the Microscribe. The measurement of the angle degree was carried out by the Rhinoceros 5.0 software (Appendix VII). The measurement method of the angle degree was obtained from the three dimensional as illustrated in (Figure 2.6). All the measurements were repeated twice by two different observers to decrease subjectivity. Similarly, these angles were converted to acute angles below the horizontal line to be more convenient. Photos have been taken at this stage of the dissection by the Canon camera (EOS, 40D; Appendix V) for documentation purposes. The three dimensional models of both superficial and deep fibres of the laminae of the posterior layer of the TLF allow direct visualization of the multiple fascial layers, which is impossible to achieve in any other way. The obtained results from this small sample will be compared to the measurement data obtained by the ImageJ software (Rasband, 1997-2014) for the same fibres.

In the L1 and L2 regions, the measurements were ignored because it was hard to determine the fibres of the deep lamina. These deep fibres were not well developed at the first two lumbar levels. To decrease inter-observer, each measurement was repeated twice at two different times and the two sets of the measurements were compared by the paired t-test. Also each measurement was repeated by another student and a similar t-test comparison was applied in order to minimize inter-observer errors.

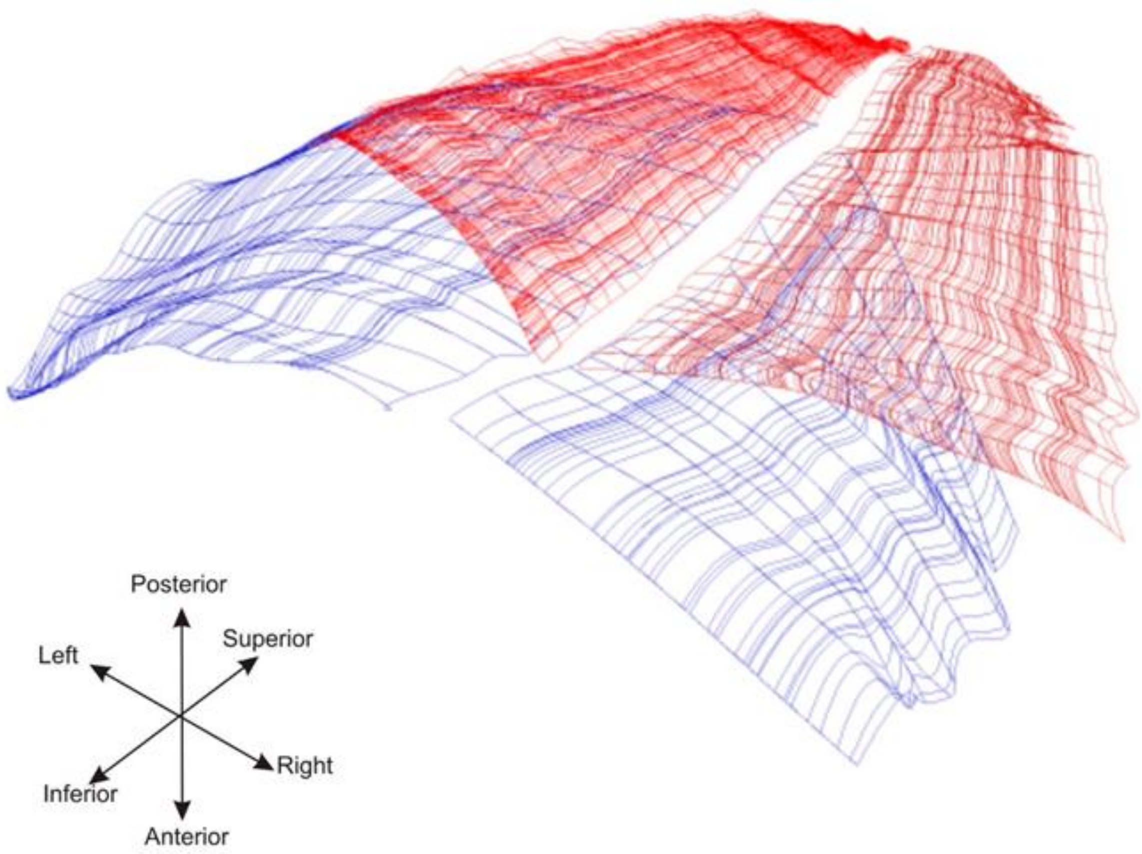

Figure 2.5 Three dimensional model of the superficial and deep fibres of the posterior layer of the TLF. The deep lamina (blue) is well developed, only inferior to the L3 level. Its fibres arise from the spinous process and are directed inferolaterally, whereas the superficial lamina (red) is more extensively established and directed inferomedially mainly from the latissimus dorsi aponeurosis toward the midline.

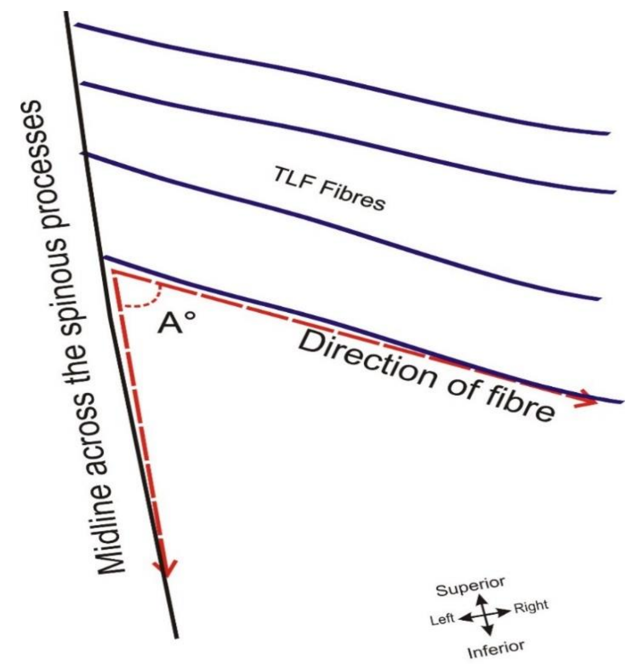

Figure 2.6 Schematic representation from the three dimensional model of the deep fibres of the posterior layer of the TLF. The measured angle (A°) of the TLF fibre direction is done by two referencing lines. The oblique line is the fibre direction and the black line is the best line applied to the lumbar spinous processes in the midline.

2.2.4 The lateral myofascial connections

The lateral margin of the TLF was exposed via serial reduction dissections from anterior and posterior approaches to explore the region between the transversus abdominis muscle and the lumbar para-spinal muscles. The dissected sections have been photographed at this stage of the dissection by the Canon camera (EOS, 40D; Appendix V). Findings of the dissected sections were compared with photos from previous dissections (Mclain, 2006; Bellini *et al.*, 2007) in order to characterize the myofascial constituents at the lateral border of the TLF.

2.3 The morphology of the lumbar para-spinal muscles

2.3.1 Specimens

Twenty five lumbar regions were taken from the cadavers of donors (twelve male, thirteen female; 80.7 ± 9.9 years; weight: 66.9 ± 14.7 kg; height: 166.7 ± 7.0 cm). One only was embalmed with salt-solution, while all the remaining cadavers were embalmed according to the standard embalming process of the Laboratory of Human Anatomy, School of life Sciences, University of Glasgow (Appendix I). Permission for the use of the cadavers and specimens, was granted by the lead anatomy license holder of the University under the terms of the Anatomy Act (1989) and the Human Tissue (Scotland, 2006) amendments.

The specimens were dissected using standard surgical equipment and with the aid of six-time magnification surgical microscope. High intensity lighting was used to ensure optimal visualisation of the specimens at all times. Following the removal of the skin and the bilaminar posterior layer of the TLF, the criteria for dissection was as follows: each muscle fibre was identified first and traced until its target attachment: bones, fascia, aponeurosis, tendon, or until it disappeared into indistinct connective tissue. The latter will be investigated histologically to find the type of attachment. Then the lumbar paravertebral muscles were carefully inspected for any gross deformity, pattern of fibre arrangement and muscular compartment. For documentation purposes, photos were taken by the Canon camera (EOS, 40D; Appendix V).

One side of each specimen was chosen arbitrarily and kept for a specific procedure. Thus one side was analysed by gross dissection, the analysis of which has been discussed already about the superficial myofascial connections, while, the other side was preserved for histological analysis.

2.3.2 The direction of the muscle fibres

The determination procedure of the direction of the superficial fibres of the MF and iliocostalis lumborum muscles was similar to one described previously (De Foa *et al,* 1989) but with some modification. After the reflection of the latissimus dorsi muscle and aponeurosis, the erector spinae aponeuroses was cut between the spinous processes and the lateral edge of the iliocostalis lumborum muscle to reveal the fibres of the underlying erector spinae muscle. Then the dissection was directed to identifying the lateral border of the iliocostalis lumborum attachment to the 12th rib. Reference lines were demarcated by inserting pins into two specific points; the first one into the lateral border of the iliocostalis lumborum attachment to the 12th rib, while the second pin was put into the posterior superior iliac spine (Figure 2.7). Photographs were captured for documentation and to be processed later by the ImageJ programme (Rasband, 1997-2014). This study considered the posterior midline as the vertical reference line in order to measure the angle of deviation from the spine. One of the specimens was excluded from this angle measurement due to a very short lumbar region. All measurements were repeated twice using each software programme, at two different times. Also the measurements were repeated by another PhD student. The assessor was blinded to all the earlier measurements. The t-test analysis was used to compare the sets of data in order to decrease the intra-observer and inter-observer errors.

Careful and thorough inspection of the bundle patterns of the MF muscle was carried out. The gross dissection was resumed with resection of the lumbar erector spinae muscle. Observation of the attachments of the MF muscle to the erector spinae aponeurosis near the midline was taken into consideration to preserve this part of the MF muscle. Reference lines were demarcated by inserting pins into the tips of the lumbar spines. These pins represented the posterior midline of the lumbar region as the vertical reference. Another pin was put into the posterior superior iliac spine (Figure 2.8). Photographs were captured for documentation and to be processed later by the ImageJ programme (Rasband, 1997-2014).

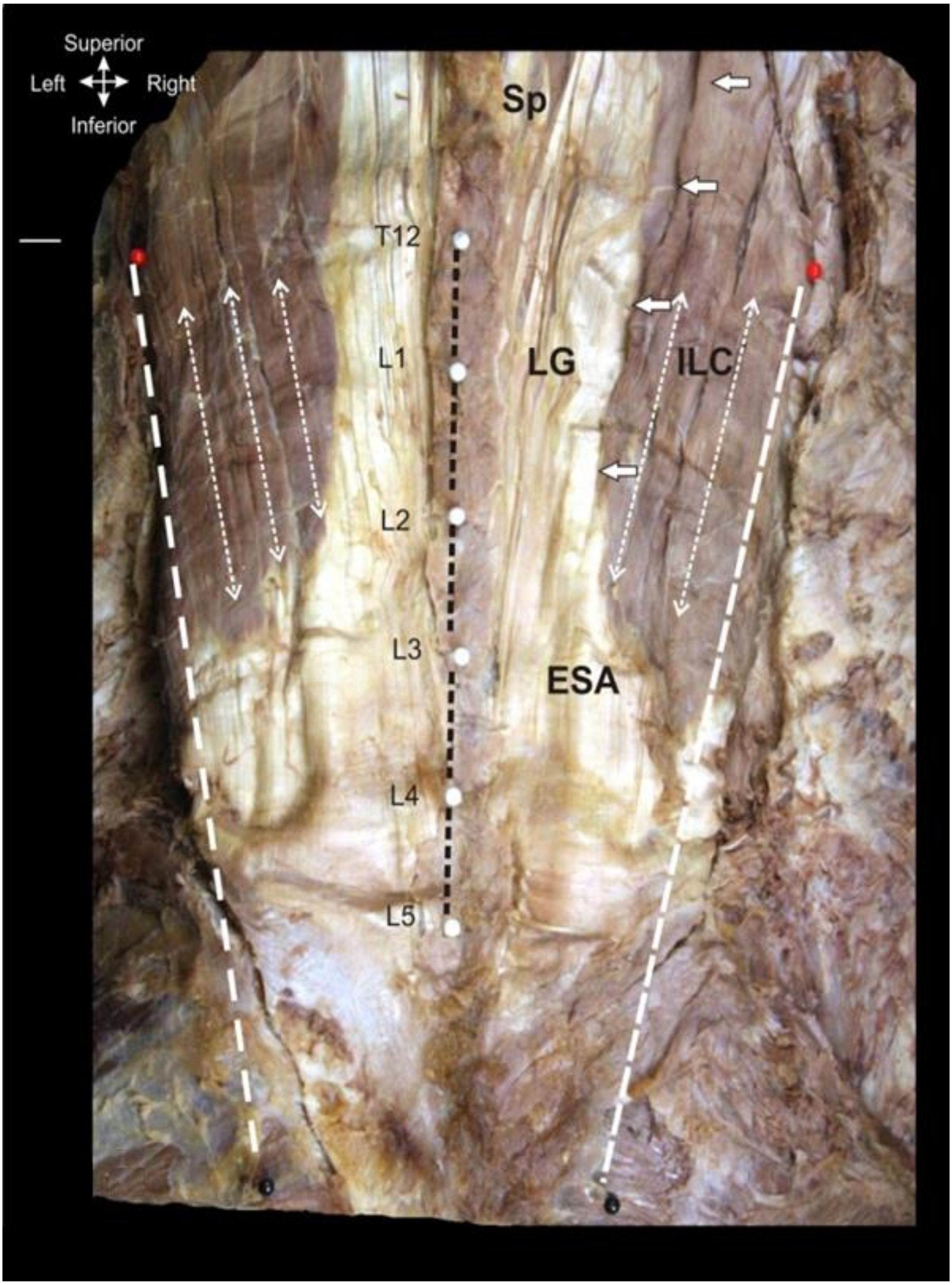

Figure 2.7 Illustrates the measuring procedure of the direction of the iliocostalis lumborum and the MF muscles. Pins were put into specific points; the red pins were inserted at the attachment of the lateral border of the iliocostalis lumborum muscle to the 12th rib, while, the black pins were inserted at the distal attachment of the iliocostalis lumborum muscle to the superior posterior iliac spine. Scale bar = 1 cm.

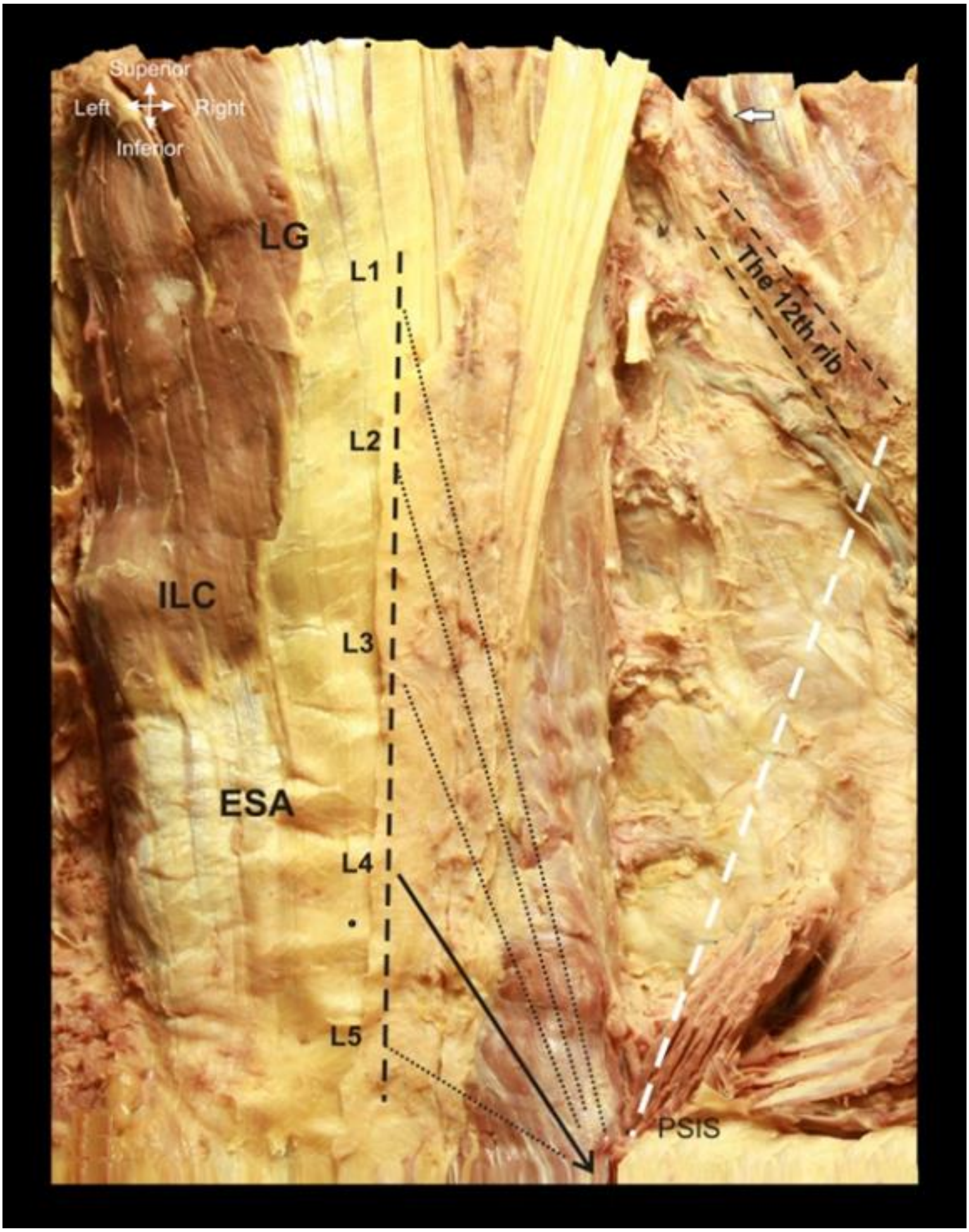

Figure 2.8 The iliocostalis lumborum and longissimus muscles were removed to uncover the MF muscle. Five references lines were drawn from the interspinous spaces L1-L5 and the superior posterior iliac spine.

2.3.3 The surface area of the attachment of the para-spinal muscles

The inter-spinalis muscles were identified in the inter-spinous spaces and are attached to the subjacent spinous processes. The tendons of the MF, iliocostalis lumborum muscle and longissimus muscles were followed to their attachments to the spinous process, the transverse process and the accessory process of the lumbar spines respectively.

Foot prints of the MF, inter-spinalis, iliocostalis lumborum and longissimus muscles were marked by permanent markers and documented. The surface area of the inter-spinalis muscle attachment was defined as the whole muscle between the two subjacent spinous processes. The attachment of the MF muscle was limited to the spinous process and the superior articular facet. The most distal attachments of the MF muscle were also noted into the dorsum of the sacrum and the iliac bones. The longissimus muscle surface area was outlined on the accessory process and the root of the transverse process, while the iliocostalis lumborum muscle was variable into the middle layer of the TLF near the transverse process. In this study only 15 specimens were used to measure the surface area of the iliocostalis lumborum muscle (Figure 2.9).

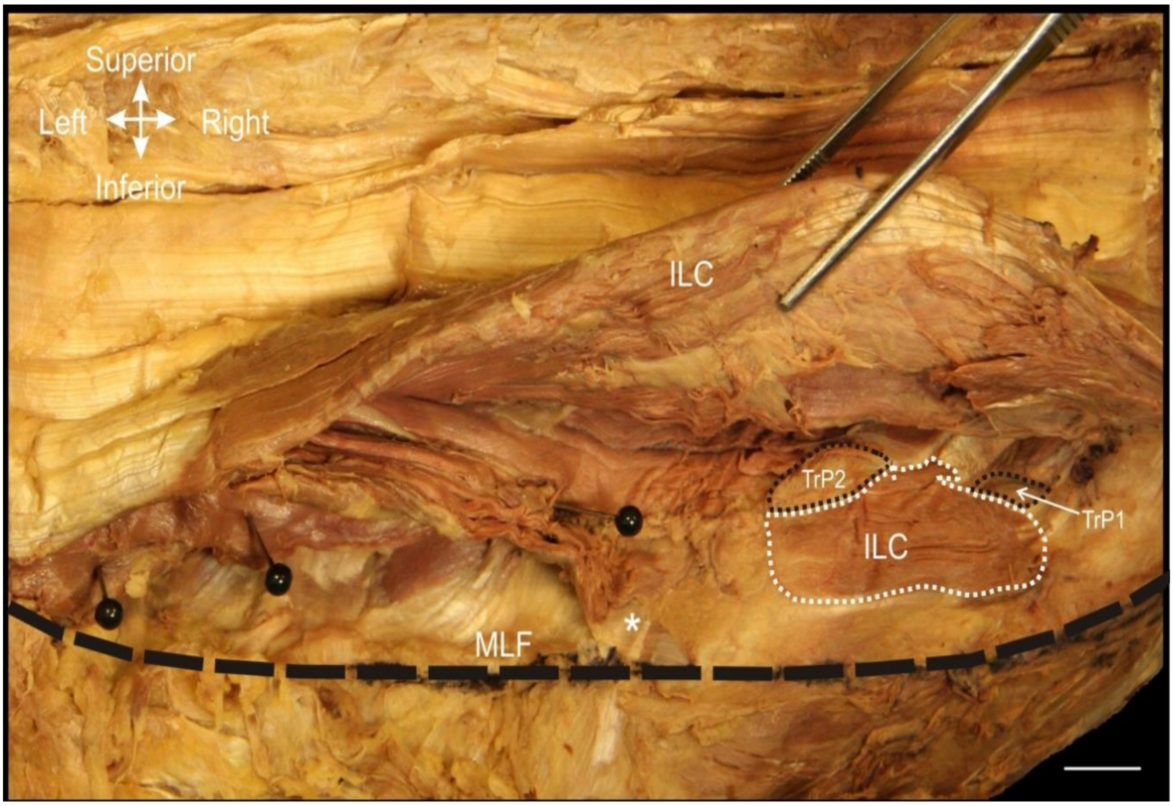

Figure 2.9 The lateral border of iliocostalis lumborum (ILC) muscle was cut from its loose attachment to the middle layer (MLF) of the TLF (Interrupted black line) and reflected by the forceps. The underlying bundles of the muscle (three black pins) were attached to the first and second transverse processes (TrP1 and TrP2). Many of the fibres were fused into the MLF (*) in the L1 and L2 levels. Scale bar = 1cm.

2.3.4 The cross-sectional area of the multifidus muscle

After the inspection of the MF muscle, the muscle was resected at its proximal attachment to the tips of the spinous processes and its distal attachments were noted at each vertebral level, specifically all the attachments to the mammillary process and superior articular process. All the MF muscle attachments to the spinous processes and the articular processes were resected. The whole segment of the MF muscle was excised and serial cross sections were done at four levels: L2-L3, L3-L4, L4-L5 and L5-S1 (Figure 2.10). Photos were taken by the Canon camera (EOS, 40D; Appendix V) for documentation purpose. The measurement of the cross-sectional area of the MF muscle was done using the ImageJ software (Rasband, 1997-2014).

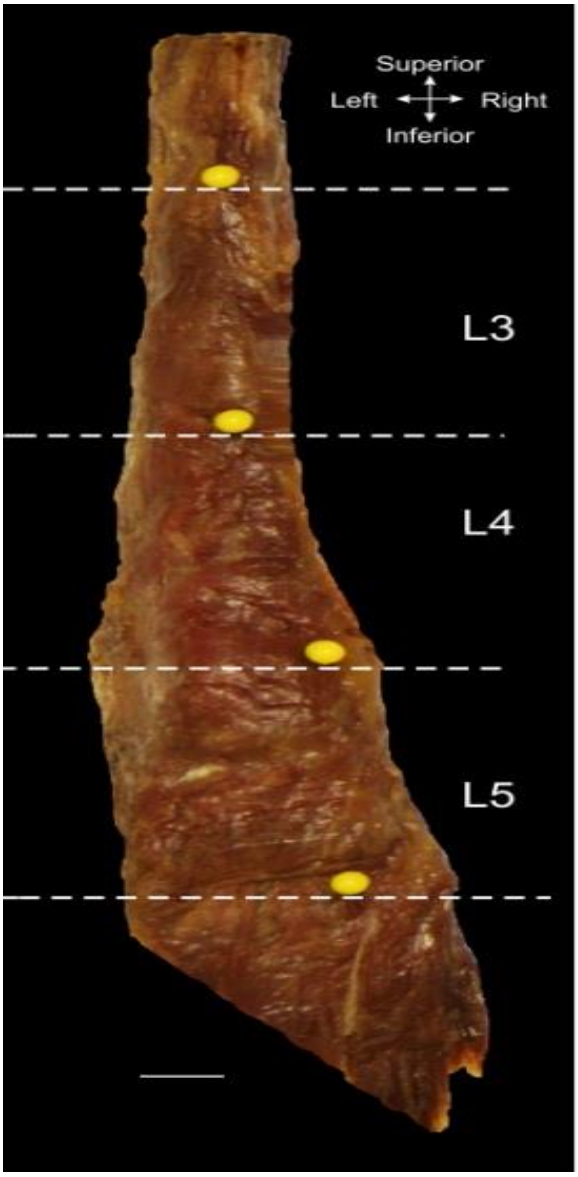

Figure 2.10 Segment of the right MF muscle to be cut in four intervertebral levels. Scale bar = 1cm.

2.4 Histologic study of the lumbar muscles attachment

2.4.1 Specimens

The specimens were excised from the cadaveric donors (twelve male, thirteen female; 80.7 ± 9.9 years; weight: 66.9 ± 14.7 kg; height: 166.7 ± 7.0 cm). The cadavers were arbitrarily selected from the Laboratory of Human Anatomy, the University of Glasgow. All donors were previously embalmed through the normal procedures of the Laboratory of Human Anatomy (Appendix I). Permission for the use of the cadavers and specimens was granted by the lead anatomy license holder of the University under the terms of the Anatomy Act (1989) and the Human Tissue (Scotland, 2006) amendments. The specimens were resected from the bodies by manual saw; specimens were dissected using standard surgical equipment and with the aid of six-time magnification surgical microscopes. High intensity lighting was used to ensure maximum visualisation of the specimens at all times.

After the resection of the TLF and the erector spinae muscle to clear the viewing of the dorsum of the transverse process from its medial root with the accessory process till its lateral tip, the attachments of the longissimus muscle and the iliocostalis muscle were foot printed and the appropriate photos were taken to measure the surface area by the ImageJ software (Rasband, 1997-2014). The criteria for dissection was as follows: each muscle fibre was first identified and followed until it attached to a bone, fuse with other muscle, fascia, aponeurosis or continued as a tendon, or disappeared into indistinct connective tissue. Then the lumbar paravertebral muscles from the preserved side were carefully inspected for any deformity and pattern of fibre arrangement in the attachment site between a tendon of muscle and a bone. The tendon was resected leaving a short stump of tendon on the bone for decalcification processing.

2.4.2 Bone and soft tissue block resection

Blocks of bones with the surrounding soft tissue were excised from the intended sites for investigation: the tips of the transverse process, the spinous process, the accessory and the articular processes. All blocks were processed for the histological study. The bony blocks obtained from the selected specimens were cut in similar fashion to minimise the amount of tissue to process, and to allow each specimen block to be accurately orientated on the rotatory microtome. The transverse processes were cut one centimetre medial to their tip. The spinous processes were cut via an oblique cut from the dorsum of the spinous process to its inferior edge. The superior and inferior articular processes were cut to get the whole facet joint intact. Finally, the accessory processes were excised by making a sagittal cut one centimetre lateral to the root of the transverse process.

2.4.3 Decalcification process

The selected blocks were decalcified, double-embedded in paraffin wax and cast in individually-manufactured moulds, as described in Appendix II. The sectioning and staining processes and their rationale are described in Appendices III and IV respectively. Digital images of each slide were taken as described in Appendix V.

Chapter 3

Results

3.1 Three dimensional measurements of the lumbar facets

3.1.1 Gross observation

The fifty sets of the lumbar vertebrae were carefully and thoroughly inspected for any deformity, degenerative changes or osteophyte formations. Particular attention was focused on the superior and inferior articular facets prior to reconstruction with the Microscribe device. Most of the articular facets and vertebral bodies had degenerative changes. A high incidence of degenerative changes was noted among all sets of lumbar vertebrae. In addition, a shortening of the vertebral body height was in 20% of the sample (Figure 3.1).

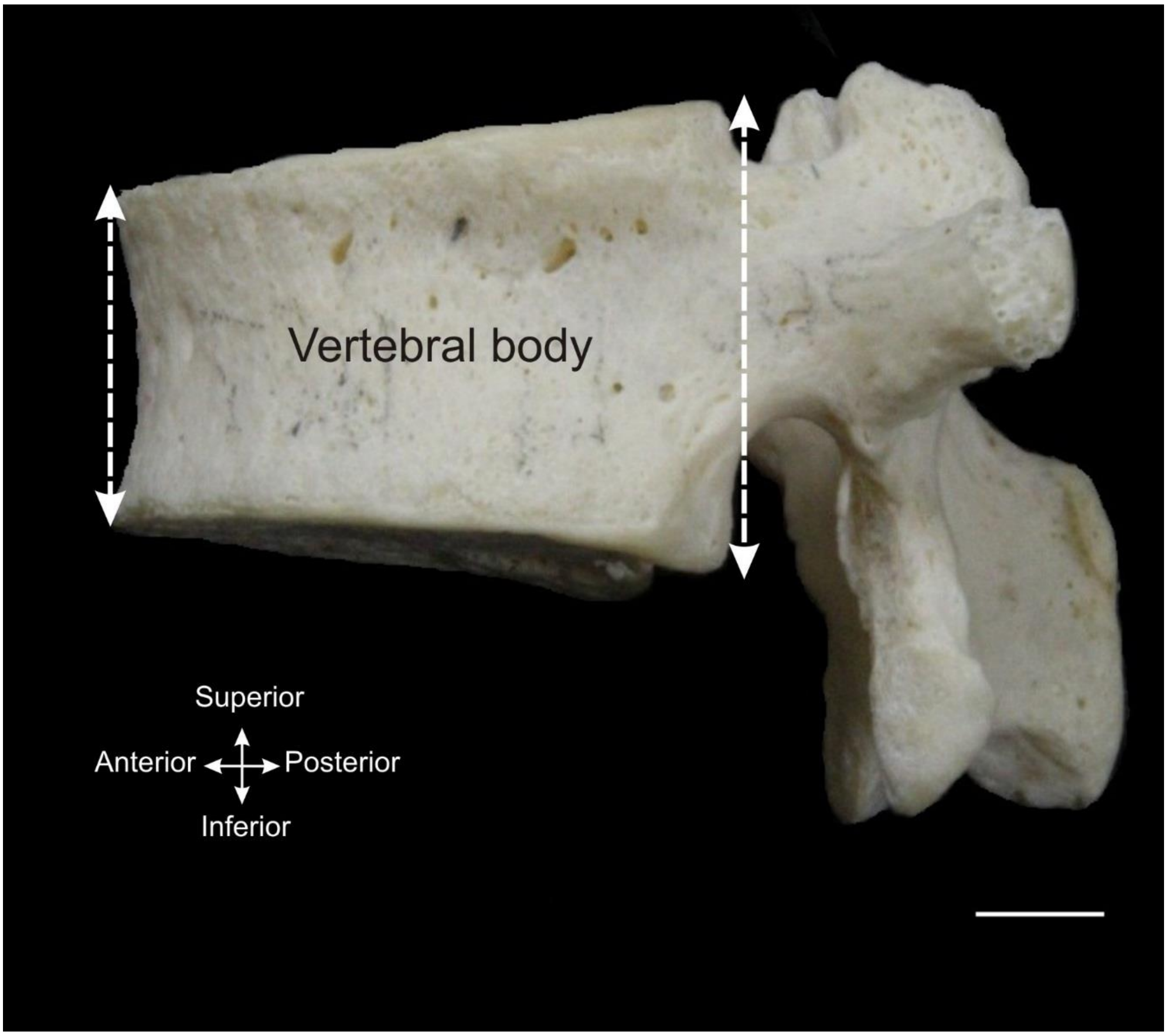

Figure 3.1 The anterior compression of the vertebral body. The height of the anterior margin is less than that in the posterior margin of the vertebral body. Scale bar = 1cm.

Marginal thickening of the vertebral body was noted in 60% of the sample and the osteophytes formation was presented in 36%. These degenerative changes were mainly predominant in the L5 vertebral body. The degenerative changes in the articular facets were 75% as marginal thickening while osteophytes formation was in 15% of the facets (Figure 3.2).

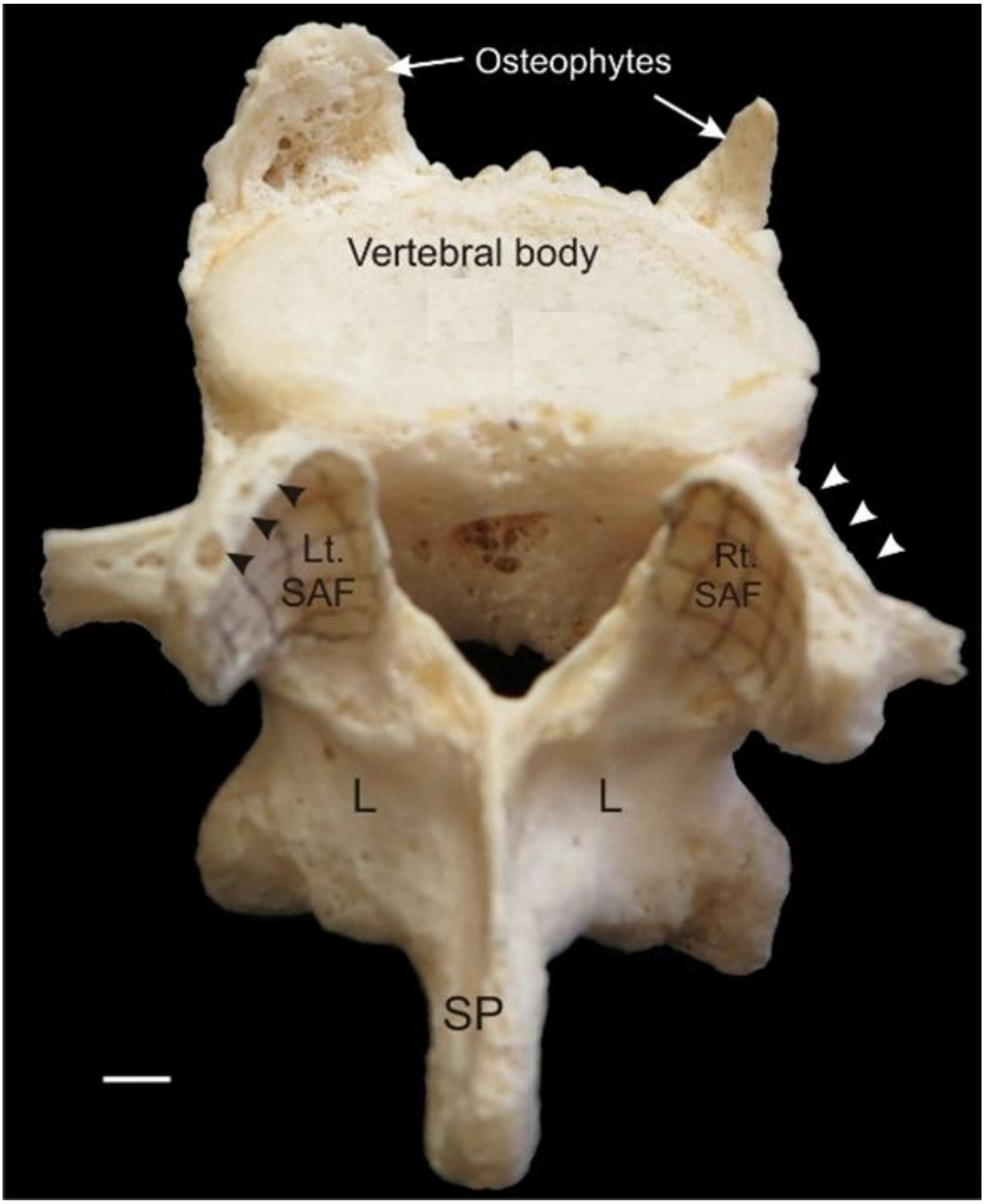

Figure 3.2 A posterosuperior view of the L5 vertebra which shows marked degenerative changes in the vertebral body and the facet processes and osteophytes extensively formed around the margin of the vertebral body. At the facet region there is marked destruction to the margin (white arrow heads in the right side and black arrow heads in the left side). Scale bar = 1cm.

3.1.2 The curvature shape of the articular facet

Different shapes of the articular facets curvatures were observed. The majority of facet surfaces assumed a curved shape, however some samples of the facets were of different shape such as C or J shapes. So, the most frequent shape was the C-shape types (67.8%), while the flat shape was noted in (25.8%). The least frequent type was the J-shape (6.4%; Table 3.1). In relation to the vertebral level, the C-shape curvature was predominant (78%) in the superior facets of the L1 level, while the flat shape (46%) was found to be in the inferior facets at the L4 spine. The J shape was only noted in 14% of the superior articular facets of the L3 vertebral.

Table 3.1 The incidence and percentages of flat and curved lumbar articular facet.

	The percentage of the curvature shape of the superior and inferior articular facets						
	Facet	**'C' Shape**		**Flat**		**'J' Shape**	
L1	Sup	78	**78%**	14	14%	8	8%
	Inf	73	73%	24	24%	3	3%
L2	Sup	74	74%	19	19%	7	7%
	Inf	63	63%	29	29%	8	8%
L3	Sup	72	72%	14	14%	14	**14%**
	Inf	74	74%	22	22%	4	4%
L4	Sup	71	71%	20	20%	9	9%
	Inf	51	51%	46	**46%**	3	3%
L5	Sup	69	69%	25	25%	6	6%
	Inf	53	53%	45	45%	2	2%
Total		**678**	**67.80%**	**258**	**25.80%**	**64**	**6.40%**

3.1.3 The surface area of the articular facet

The mean facet articular surface area revealed a gradual increment toward the lower vertebral levels (Figure 3.3). The mean surface area was greatest in the fifth lumbar vertebra (174.5 ± mm^2 39.9) and hence the least was in the first lumbar vertebral (115.0 ± mm^2 33.39). The ANOVA analysis revealed that the surface area in the fifth vertebral level was only significantly different ($p<0.05$) from that in the L1 and L2 levels (143 ± 43.29 mm^2). In comparing the means of the first and the second lumbar facet areas, the t-test revealed significant difference between the two means ($p<0.05$), whereas no significant difference was noted among the inferior three lumbar levels.

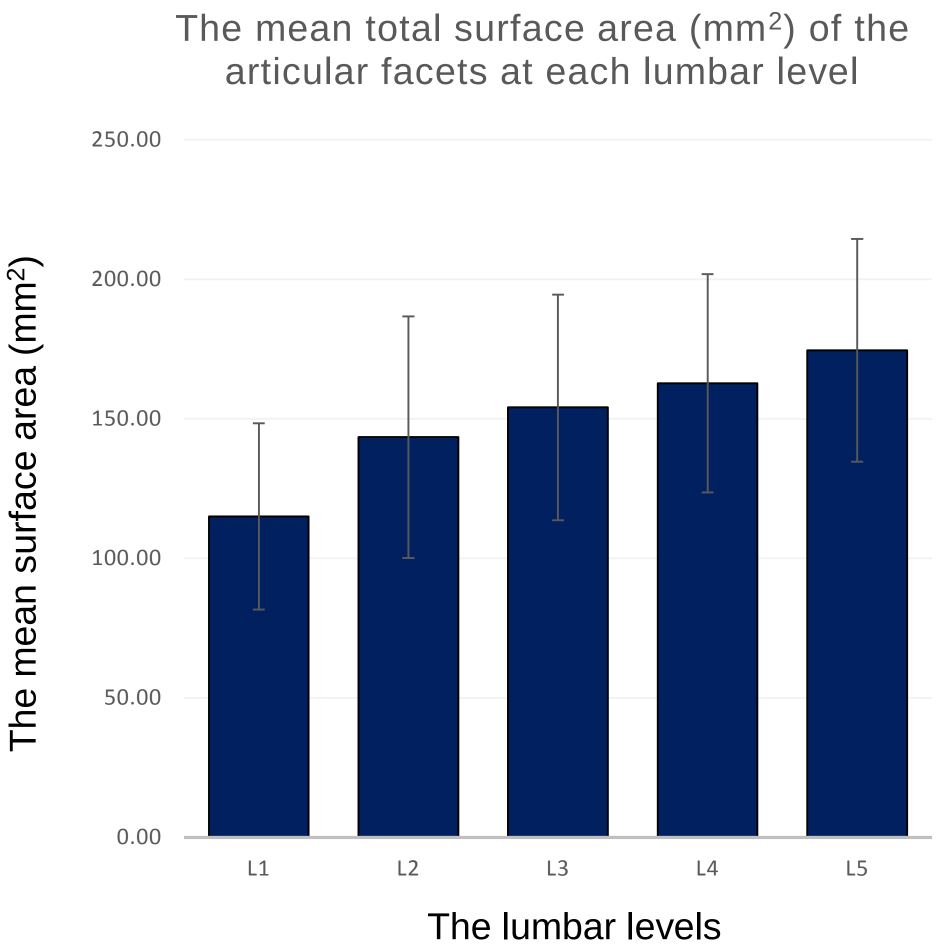

Figure 3.3 The mean facet surface area (mm^2) for each lumbar vertebral level.

Comparing the surface area of the superior and the inferior lumbar facets revealed the same pattern of the gradual increment towards the inferior lumbar levels. In t-test analysis there was only significant difference between the mean surface area of the superior and inferior lumbar articular facets at the L3 and L4 levels ($p<0.05$), while no significant difference was noted between the mean surface areas of the superior and inferior lumbar articular facets at the L1, L2 and L5 lumbar levels (Figure 3.4).

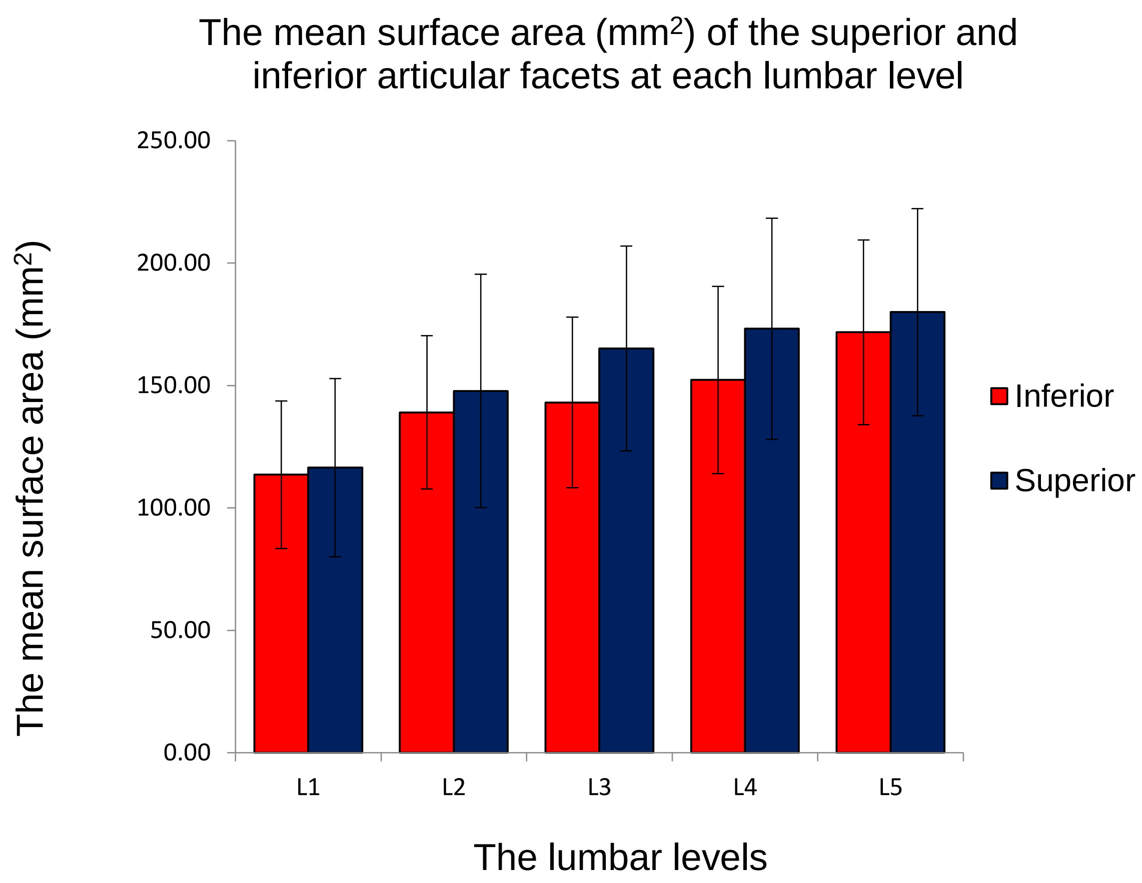

Figure 3.4 The mean comparison of facet area (mm^2) between the superior and inferior facets for each lumbar vertebral level.

3.1.4 The orientation of the articular facet

There was gradual decrease in the sagittalisation degree when moving from the superior lumbar level to the inferior level. The angulation degree was more sagittal in the upper lumbar level with mean value at the L1 level of (69.0°±11.0). The mean angulation at L5 level (49.4°±11.0) was significantly ($p<0.05$) less than the angulation values in the L1 level (69.0°±11.0), the L2 level (68.4°±9.9) and the L3 level (65.7°±11.8).

ANOVA analysis did not reveal any other significant difference between the mean of orientation between the five lumbar levels (Figure 3.5).

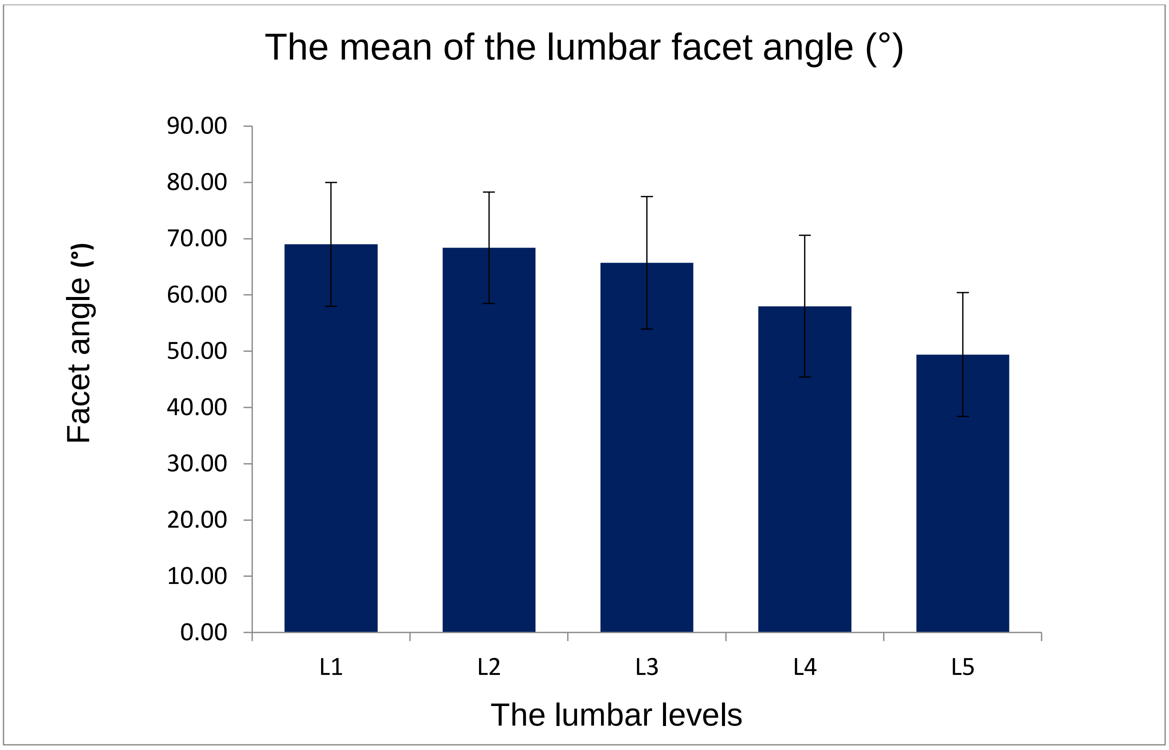

Figure 3.5 The mean facet angle degree (°) of articular facts at each lumbar level.

3.2 The superficial myofascial interactions

3.2.1 The fascial thickenings

In all specimens the posterior layer of the TLF was identified and its two sub-layers were also documented. The superficial fascia is well-defined as a continuation from the inferior part of the latissimus dorsi muscle. The fibres of the superficial lamina of the posterior layer of the TLF crossed the midline and continued to the contralateral side below the level of L4 spinous process. These crossing fibres of the superficial lamina were forming a decussation with its fellow from the opposite side (Figures 3.6 and 3.7).

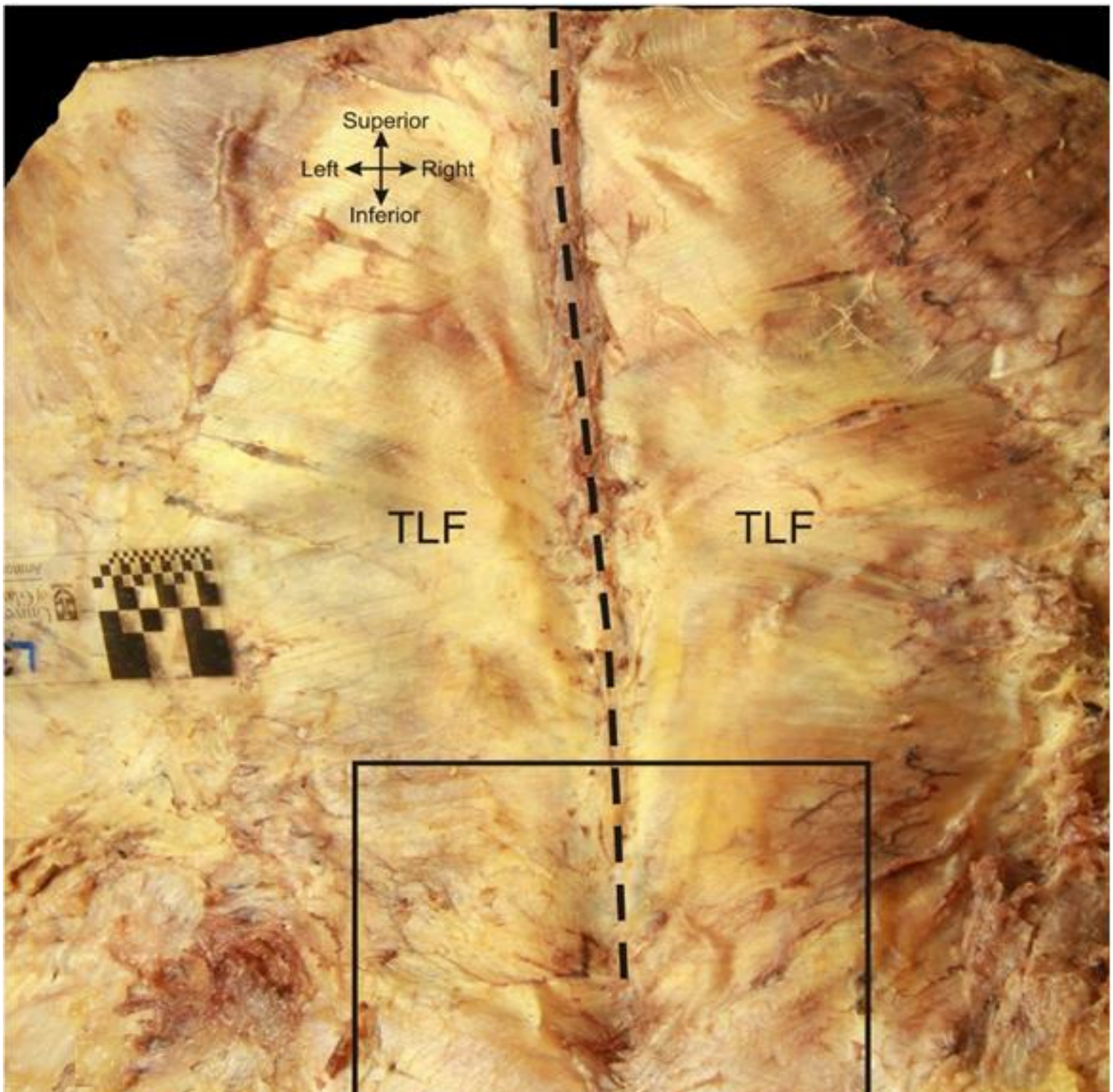

Figure 3.6 The superficial fibres of the posterior layer of the TLF decussated below the level of L4 spinous process. The decussated zone has been magnified for better illustration. Scale bar = 1 cm.

This decussation was clearly noted and documented in all specimens. While the deep lamina of the TLF (the vertebral aponeurosis) was identified as a thin loose fibrous layer. It was well identified from the mid-lumbar region (L3) and downward.

Numerous superficial fascial thickenings were noted in the lumbar and gluteal regions. There was thickening along the lumbar spinous processes from L2 down to the L4. However, it was uncertain whether this thickening was an evidence of the "posterior accessory ligaments" in the midline of the lumbar region.

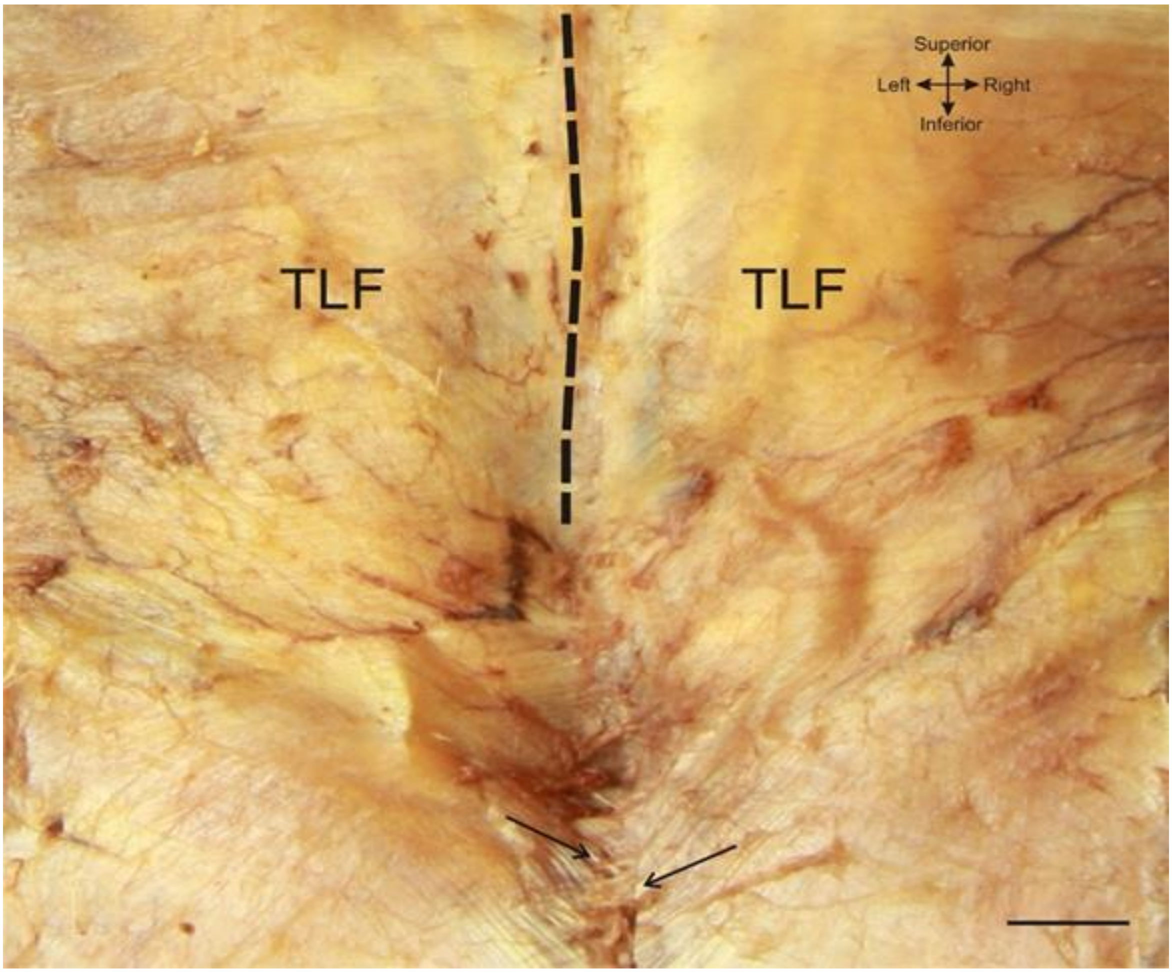

Figure 3.7 The decussation of the superficial fibres of the posterior layer of the TLF was evident in all specimens (arrows). The figure has been magnified from the previous figure (3.6). Scale bar = 1 cm.

A second thickening was also noted at the fusion site between the lateral border of the iliocostalis lumborum muscle and the middle layer of the TLF. This fusion or thickening was extended from the iliac crest up to the attachment of the iliocostalis lumborum to the 12th rib. Another thickening was clearly identified from the inferior part of the posterior layer of the TLF over the iliac crest (Figure 3.8).

3.2.2 The myofascial connections

The results noted numerous connections between, or extensions of, tissues that go beyond typical text-book descriptions of the region. Of particular interest were the increased connections between lumbar and gluteal regions, both through muscular and connective tissues. From the lumbar region this was largely via the fascial floor supporting the inferior parts of the latissimus dorsi muscle; these either merged with gluteal fascia, or were strongly adherent to the iliac crest (n = 20; 80%; Figure 3.8).

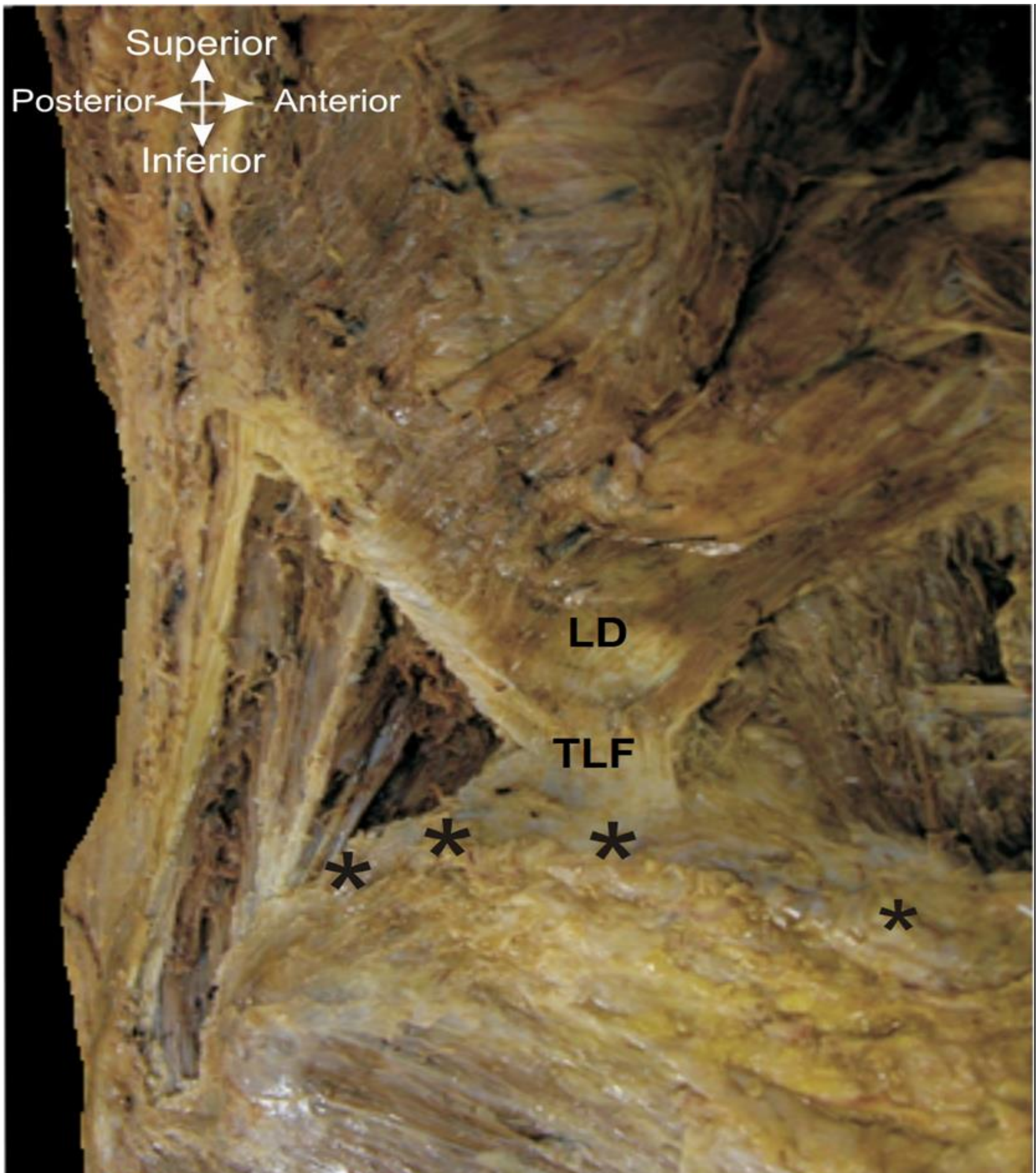

Figure 3.8 Lateral view of the right gluteal region, demonstrating the superficial connections of the latissimus dorsi (LD) via the thoracolumbar fascia (TLF) to the iliac crest (*).

Another variety of the superficial myofascial connection was from the gluteal region. This connection was the superior extension of the gluteus maximus muscle over the sacroiliac joint line (n = 5; 20%; Figure 3.9).

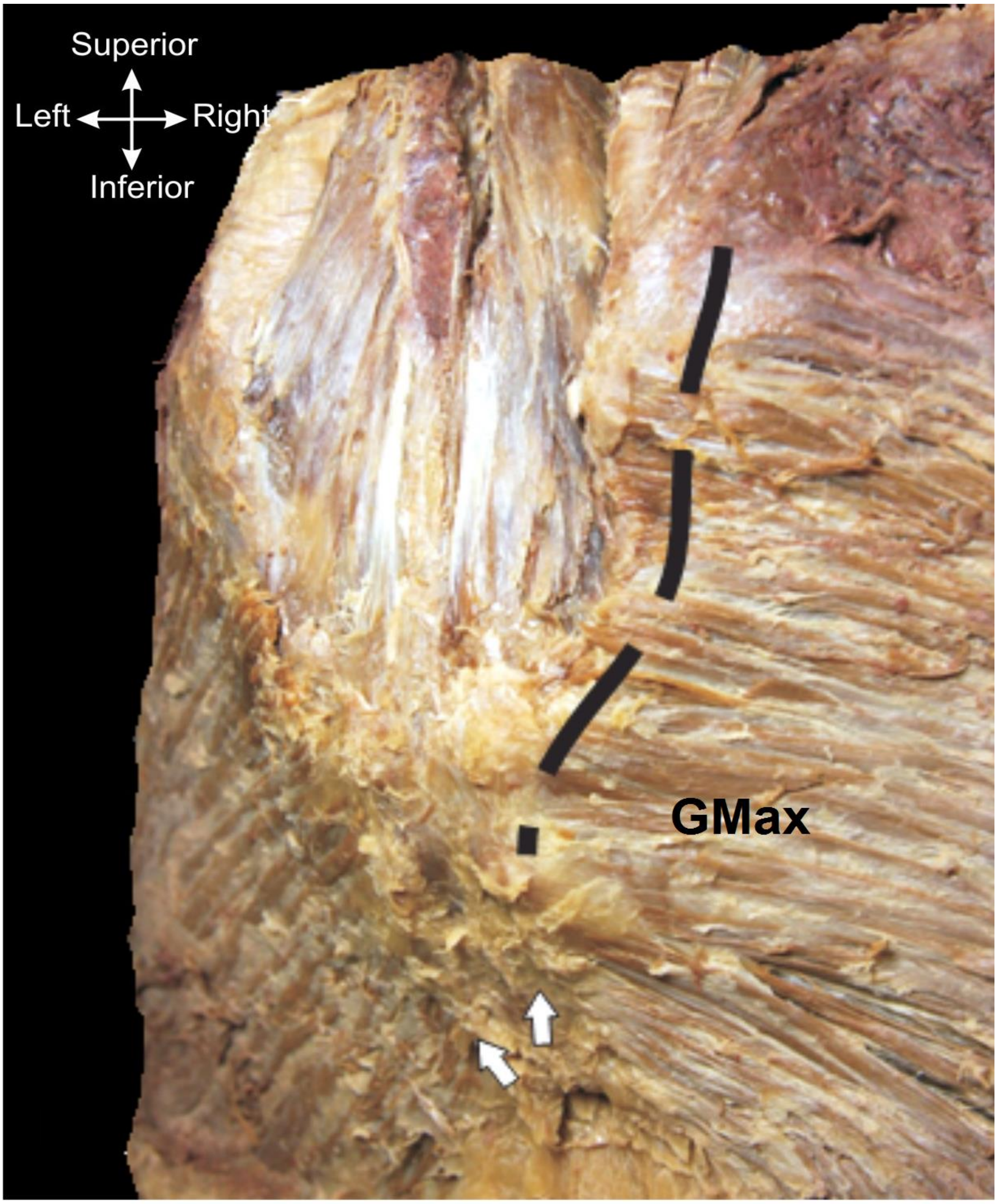

Figure 3.9 The gluteus maximus muscle (GMax) crosses the sacroiliac joint line (dotted line) before merging with the posterior layer of the thoracolumbar fascia (cut). More inferiorly (arrows) opposing muscles interdigitating in 20% of the specimens.

The thickened posterior layer of the TLF on its lateral margins, is an indication of strong interactions with the adjacent muscle. This fascial thickening was noted in all specimens. This thickening was composed of all layers of the TLF which fused together into a thick fascial composite that attached firmly to the iliac crest, the posterior superior iliac spine and the sacrotuberous ligament (Figure 3.10).

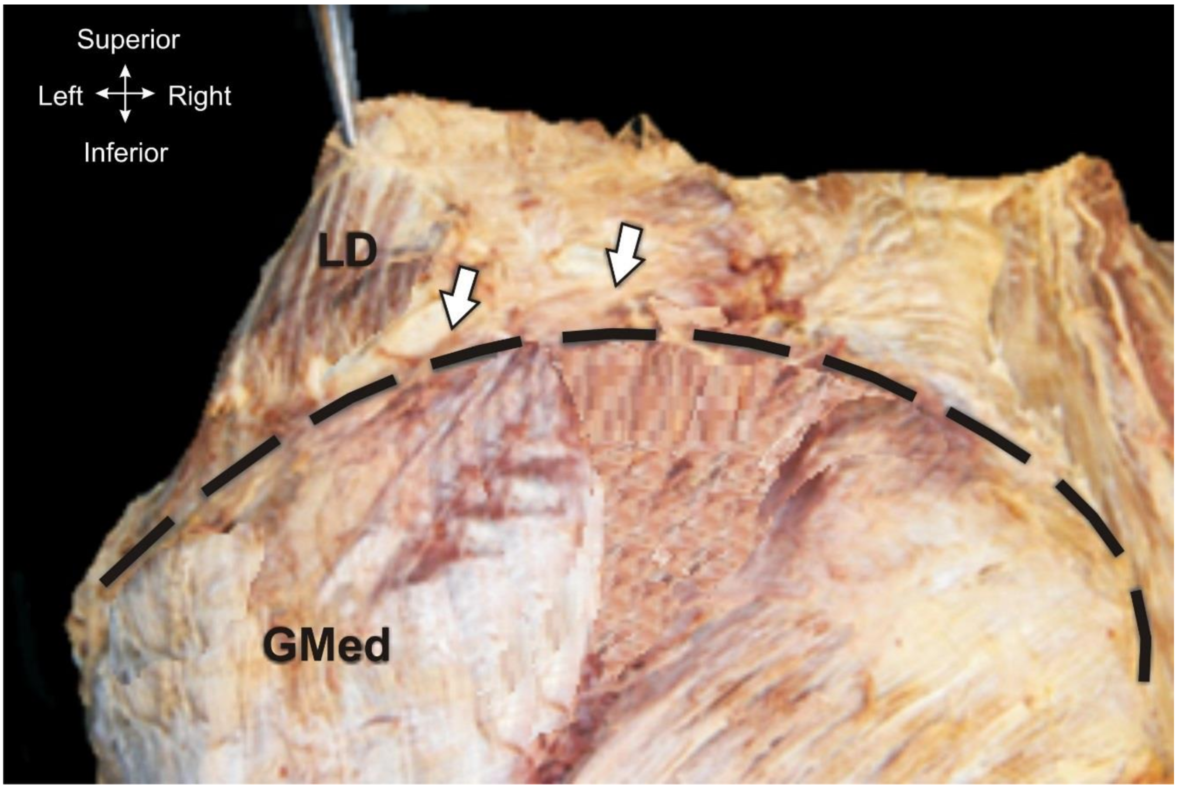

Figure 3.10 Posterior view of the left gluteal region. The iliac crest (dotted line) is a point of convergence with latissimus dorsi (LD) and gluteus medius (GMed) muscles interdigitating. The gluteus medius muscle also merges with connective tissue from the TLF (arrows).

3.2.3 The lateral raphe and the interfacial triangle

The lateral thickening of the TLF was clearly observed bilaterally along the lateral border of the iliocostalis lumborum muscle in all specimens. A fascial reflection from the posterior layer of the TLF separated between the iliocostalis lumborum muscle and the longissimus muscle. The superficial lamina of the posterior layer of the TLF was merged superiorly with the aponeuroses of the latissimus dorsi muscle and the serratus posterior inferior muscle (Figure 3.11). The anterior divisions from the aponeurosis of the transversus abdominis muscle and the internal oblique muscle were fused and become continuous with the deep lamina of the posterior layer of the TLF. This fascial fusion or thickening forms the posterior wall of a potential inter-fascial space known as lumbar inter-fascial triangle.

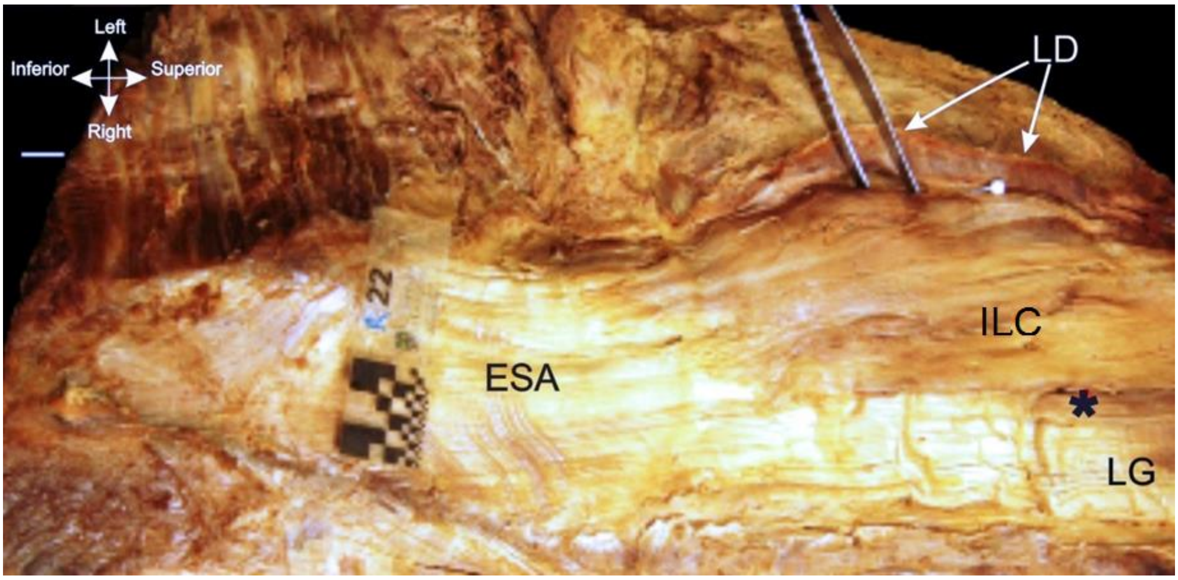

Figure 3.11 The TLF was resected at its continuation with the latissimus dorsi muscle (LD) in the left lumbar region and the lateral thickened cut margin was reflected by the forceps. The anterior layer of the aponeurosis of the transversus abdominis muscle and the internal oblique muscle was continuous with the posterior layer of the TLF (white pin). This layer was partially bisected to show the potential space of the lumbar inter-fascial triangle (forceps in). There was a cleft (*) between the iliocostalis lumborum (ILC) muscle and the longissimus muscle (LG). Scale bar = 1cm.

The deep lamina of the posterior layer of the TLF covered the para-spinal muscles posteriorly while the middle layer of the TLF lined the iliocostalis lumborum muscle anteriorly (Figure 3.12).

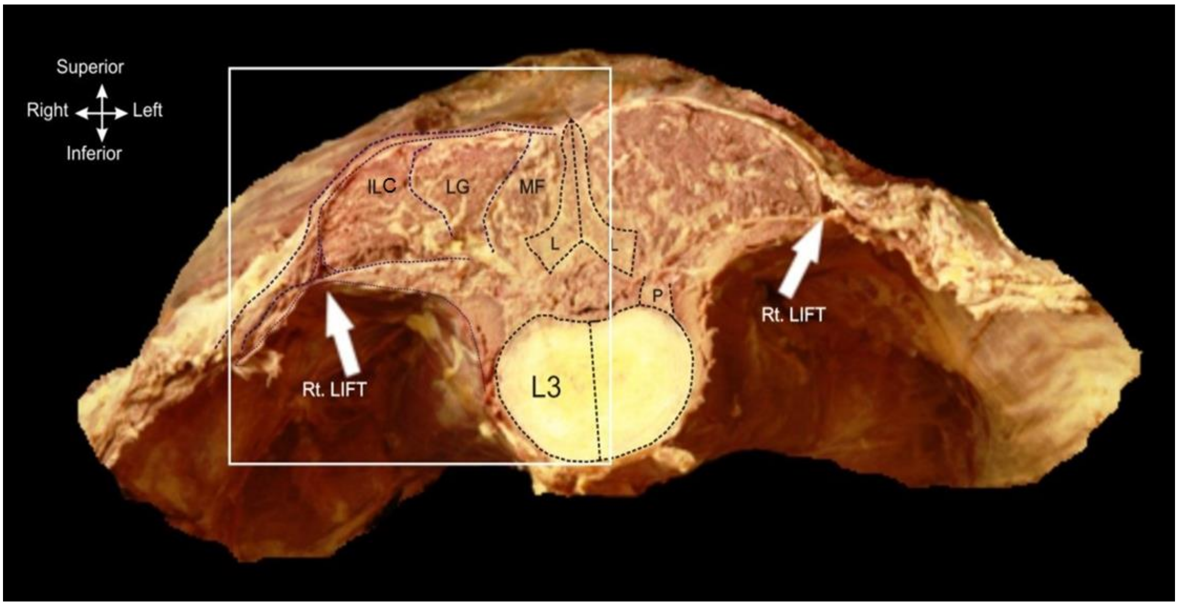

Figure 3.12 Cross sectional dissection at the level of L3 shows the lateral inter-fascial triangle (LIFT; white arrow). The LIFT was clearly identified in 16 out of 25 specimens (64%). The middle and the posterior layers of the TLF (blue dotted line) were covering the para-spinal muscles: the multifidus (MF), longissimus (LG) and iliocostalis lumborum (ILC). Part of the pedicle has been shown in this section.

This covering sheath is known as the para-spinal retinacular sheath. Along the lateral border of the para-spinal retinacular sheath, a thickened line or a raphe was formed where the sheath met the aponeurosis of the transversus abdominis muscle and internal oblique muscles. This lateral raphe is a thickened convergence of fascial fusion and it was identified bilaterally in all specimens. No sufficient evidence was observed to suggest the existence of a para-spinal muscles compartment. Nevertheless, a partial compartmentisation could be noted from the cross sectional dissection (Figure 3.13).

The thickened lateral margin of the TLF was illustrated by serial dissections. The sections were examined to explore the area between the transversus abdominis internal oblique aponeurosis and the para-spinal muscles. It was documented that the para-spinal muscles are encapsulated by a continuous para-spinal retinacular sheath (Figures 3.12 and 3.13) which was composed of the deep lamina of the posterior layer of the TLF.

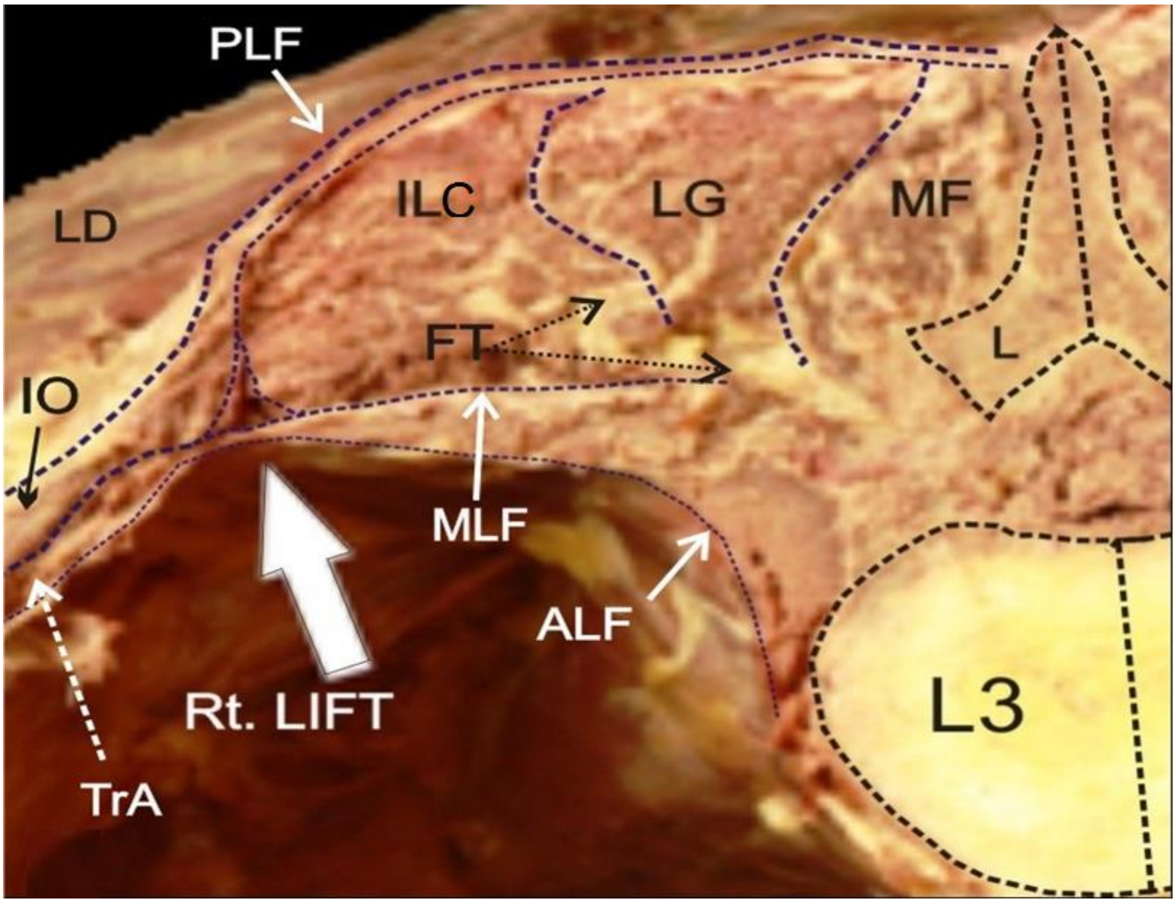

Figure 3.13 A magnified zone from figure 3.12 shows the posterior layer (PLF) of the TLF covers the para-spinal muscles. The PLF and the middle layer (MLF) of the TLF made an osteo-fascial space from the spinous process to the transverse process. The fatty tissue (FT) was also noted in this space. The MLF fused with the anterior layer (ALF) of TLF at the anterior wall of the LIFT.

This sheath extended from the spinous process to the transverse process. Thus the posterior layer and the middle layer of the TLF made an osteo-fascial space from the spinous process to the transverse process.

The lumbar inter-fascial triangle was clearly identified in 16 out of 25 specimens (64%). When the aponeurosis of the abdominal muscles reached the lateral border of the para-spinal retinacular sheath, it was divided into two discrete laminae which were continuous with the anterior and posterior walls of the para-spinal retinacular sheath. This fascial arrangement was constructed of a fat-filled lumbar inter-fascial triangle which was located along the lateral border of the para-spinal muscles from the 12th rib to the iliac crest. This fascia triangle is therefore a fusion of different fascial layers along the lateral border of the TLF.

3.2.4 Direction of the thoracolumbar fibres

The angle range of the direction of the superficial and deep fibres of the posterior layer of the TLF below the horizontal was measured by ImageJ software (Rasband 1997-2014) and is listed in Table 3.2. The deep fibres were poorly identified at the lumbar levels L1 and L2, therefore their values have been ignored and are not included in the table for the first two lumbar levels.

Table 3.2 The range of angle of superficial and deep fibres of the posterior layer of the TLF measured by ImageJ software (Rasband 1997-2014).

The range of angle (°) below the horizontal of the fibres direction of the posterior layer of the TLF		
Lumbar levels	Superficial fibres	Deep fibres
L1	9-14	*
L2	15-17	*
L3	18-22	15-20
L4	23-28	21-24
L5	29-40	25-35

* In the L1 and L2, measurements were ignored because it was hard to determine the deep fibres of the posterior layer of the TLF.

The data obtained from the three dimensional model for the superficial fibres of only the posterior layer of the TLF, were analyzed by Rhinoceros X5 software (Robert McNeel and Associates, USA). There was significant difference ($p<0.05$; t-test) in the superficial fibres between the right and left sides at the lumbar levels L2 and L4 and no difference between the sides in the remaining levels (Figure 3.14).

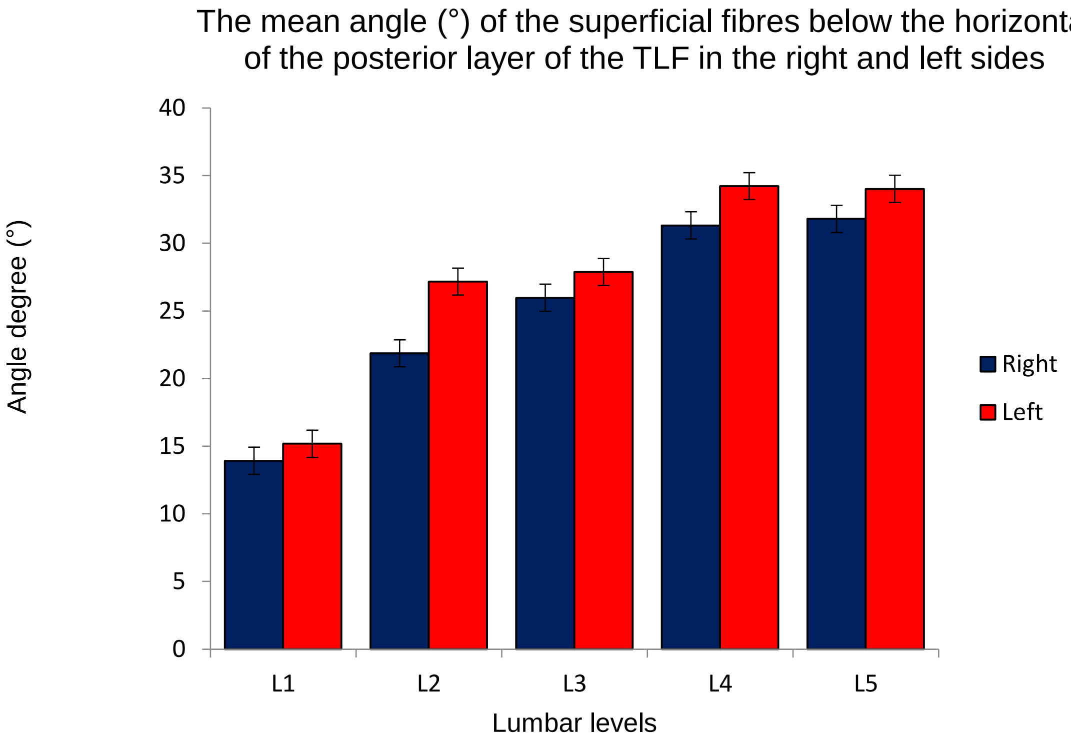

Figure 3.14 The mean of the angle direction of the superficial lamina of the posterior layer of the TLF. There was significant difference ($p<0.05$) between the right side (blue) and the left side (red).

While the mean of the angle from the three dimensional model of the deep fibres were calculated by Rhinoceros X5 software (Robert McNeel and Associates, USA), the fibres included in the measurements were those determined in the L3, L4 and L5 lumbar levels for six specimens only (Table 3.3). The paired t-test did not reveal any significant difference between the right and left sides in all three inferior lumbar levels ($p< 0.05$). The obtained results from this small sample will be compared to those measurements already achieved by ImageJ software (Rasband 1997-2014; Table 3.2).

Table 3.3 the mean of angle of the right and left deep fibres of the posterior layer of the TLF below the horizontal: measured by the rhinoceros programme.

The mean of angle (°) of the deep fibres of the posterior layer of the TLF below the horizontal		
	Deep fibres	
Lumbar levels	Right	Left
L3	22.3 ± 2.1	22.45 ± 2.7
L4	23.9 ± 4.3	24.2 ± 4.2
L5	30.02 ± 1.4	29.15 ± 1.5

3.3 The morphology of the lumbar para-spinal muscles

3.3.1 Gross observations

An asymmetrical arrangement of the MF bundles was observed in only two out of 25 specimens (8%). The asymmetry was of multi-bundle variety (Figure 3.15).

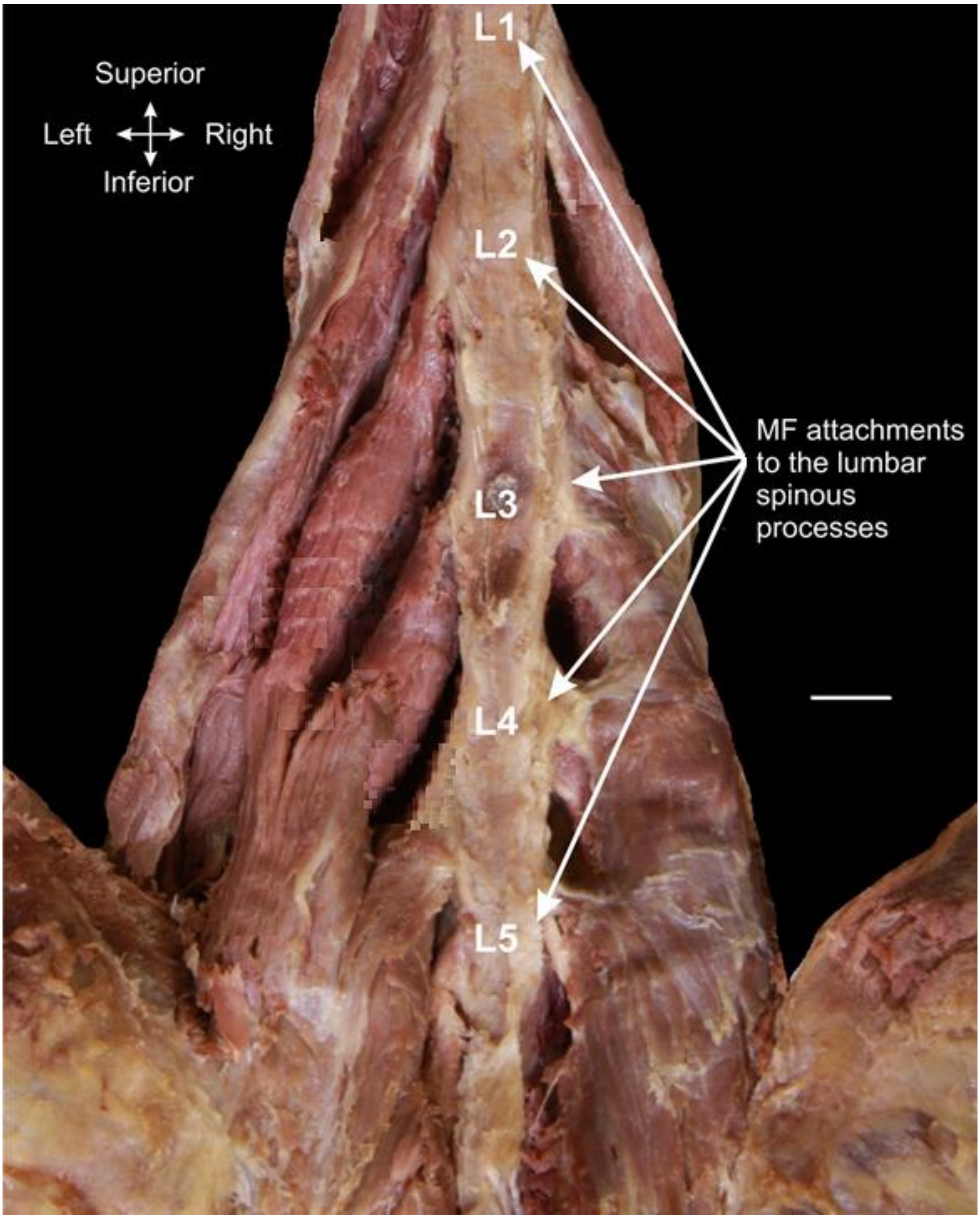

Figure 3.15 A posterior view of the Lumbar MF muscle shows the multi-bundle pattern of the fibre arrangement in the left side. Scale bar = 1cm.

In all specimens there was a clear cleft observed between the longissimus muscle and the iliocostalis lumborum muscle. No fascial lamina was noted in the cleft. Small blood vessels and nerves were founded in all specimens (Figure 3.16).

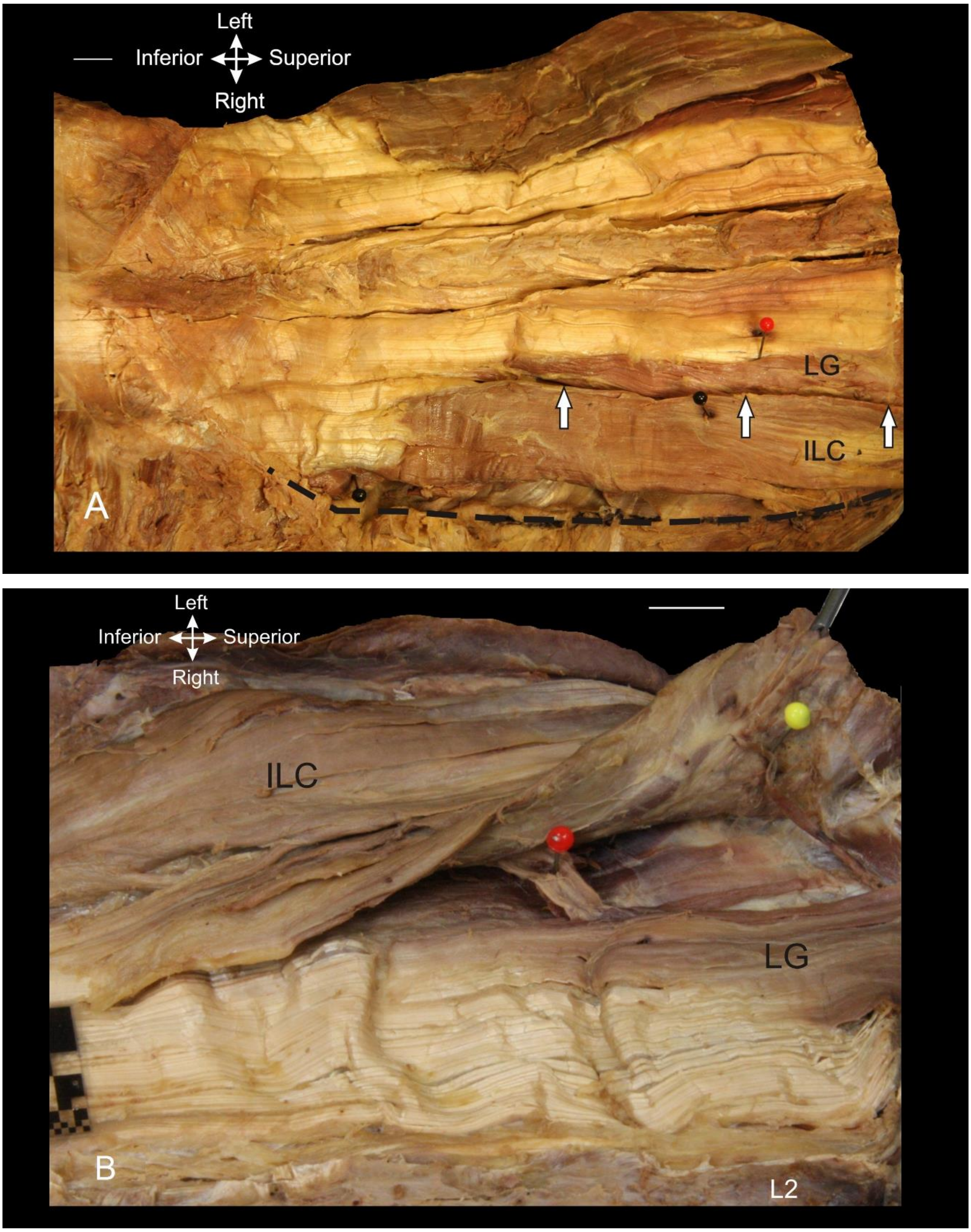

Figure 3.16 A- The right lumbar region shows the cleft (white arrows) between the longissimus (red pin) and iliocostalis lumborum muscles (black pin). The black interrupted line represents the site of the attachment of the lateral border of the iliocostalis lumborum muscle with the TLF. B- Blood vessels (red pin) and nerve (yellow pin) were observed in the cleft in all specimens. Scale bar = 1cm.

Also another inter-muscular cleft was documented between the MF muscle and the longissimus muscle, but an inter-muscular septum was clear only in 20 out of 25 specimens (80%). In cross section dissection of the MF muscle there was a variable amount of the fatty tissue observed infiltrating the MF muscle and in the inter-muscular cleft (Figure 3.17).

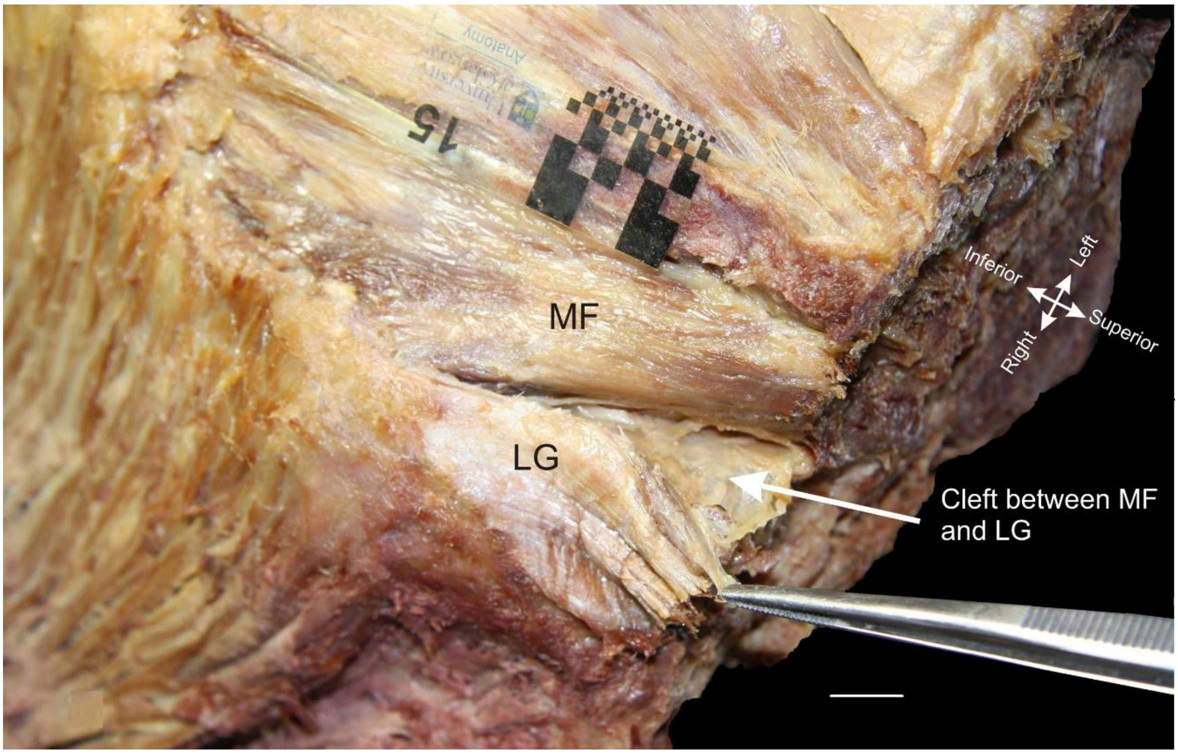

Figure 3.17 In the right lumbar region, the inter-muscular cleft between the MF muscle and the longissimus muscle was documented and was occupied by a variable amount of fatty connective tissue. Scale bar = 1cm.

The longissimus muscle was observed to be attached entirely and directly to the accessory processes and the root of the transverse process. This attachment was composed of a musculotendinous structure. No variation was noted in the insertion of the longissimus muscle to the accessory process or to the root of the transverse process (Figure 3.18). The iliocostalis lumborum muscle had a variable muscular attachment to the transverse process. In 15 out of 25 specimens the iliocostalis lumborum muscle was fused with the middle layer of the TLF near the transverse process. In ten specimens (40%) the muscle was attached directly to the transverse process (Figure 3.18B). The attachment of the muscle was diffusely into the posterior aspect of the middle layer of the TLF and it was easily separated by applying simple traction, while the attachment of the MF muscle was to the superior articular process and the tip of the lumbar spinous process (Figure 3.15).

Figure 3.18 A- The insertion of the LG muscle into the accessory process (black arrows). A zone was magnified to show the insertion of the iliocostalis lumborum muscle. B- The iliocostalis lumborum muscle inserted into the 12th rib and into the middle layer of the thoracolumbar fascia (MLF) near but not to the tip of the transverse process. Scale bar = 1cm.

3.3.2 The direction of the muscle fibres

Careful and thorough inspection of the iliocostalis lumborum muscle showed that the subjacent fascicles of the iliocostalis lumborum muscle were parallel to each other. Similarly, they were apparently descended parallel to the reference line between the posterior superior iliac spine and the intersection of the attachment of the lateral border of the iliocostalis lumborum muscle at the 12th rib (Figure 2.7). Also the MF fibres were noted to be parallel to their reference line which was defined between the posterior superior iliac spine and the L2-L3 inter-spinous space.

The mean of the angulation and deviation of the fibre directions for the MF muscle and the iliocostalis lumborum muscle in respect to their reference lines are shown in (Table 3.4).

Table 3.4 The mean of the muscle fibre direction (°) of the iliocostalis lumborum and MF muscle in men and women.

	MF muscle	Mean	STDEV
Men (n=12)	Fibre angulation from spine	16.5	1.77
	Fibre deviation angle from reference line	0.3	0.81
Women (n=12)	Fibre angulation from spine	25.4	4.98
	Fibre deviation angle from reference line	0.2	0.91
	Iliocostalis lumborum muscle		
Men (n=12)	Fibre angulation from spine	14.4	1.98
	Fibre deviation angle from reference line	0.3	0.81
Women (n=12)	Fibre angulation from spine	13.5	1.33
	Fibre deviation angle from reference line	5.1	2.84

3.3.3 The surface area of the attachments of the para-spinal muscles

The inter-spinalis muscle had the largest mean surface area (Figure 3.19). The mean surface area of the inter-spinalis muscle was significantly larger than the mean of the other three muscles: the MF, longissimus muscle and iliocostalis lumborum muscle ($p<0.05$; t-test).

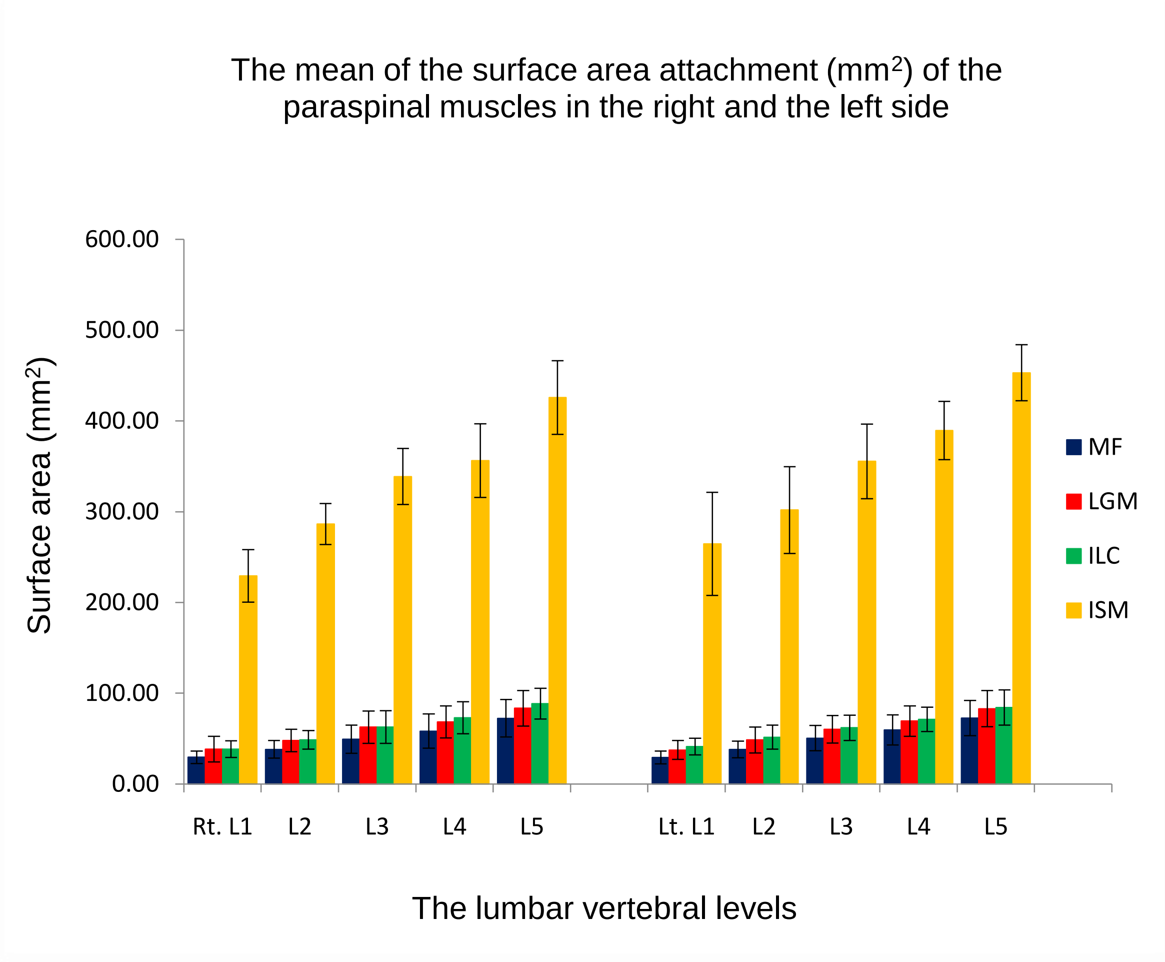

Figure 3.19 Shows the mean of the surface area attachments for the para-spinal lumbar muscles: the inter-spinalis (ISM), the iliocostalis lumborum (ILC), the longissimus (LGM) and the MF muscle in the right and left sides of the lumbar region.

No significant difference was noted among the remaining three muscles. The overall trend confirmed that the mean surface areas of the MF, longissimus muscle and iliocostalis lumborum muscle were close to each other (Table 3.5). A significant difference was noted between the sides of the lumbar region only for the attachment areas of the inter-spinalis muscle ($p<0.05$; t-test). While, for all the remaining muscles there were no significant difference between the right and left sides. So the data were summarized to the total value for each muscle excluding the iliocostalis muscle (Figure 3.20).

Table 3.5 The total mean surface area (mm^2) for the para-spinal lumbar muscles (mm^2) at each lumbar vertebral level.

The mean and standard deviation of the surface area attachments for the para-spinal lumbar muscles (mm^2)				
Lumbar levels	MF	LGM	ILC*	**ISM**
L1	29.36 ± 06.77	37.99 ± 06.35	39.80 ± 08.99	**247.00 ± 09.32**
L2	38.08 ± 09.29	48.26 ± 08.50	50.10 ± 11.93	**294.22 ± 12. 33**
L3	49.95 ± 14.41	61.40 ± 13.19	62.40 ± 16.73	**347.17 ± 17.44**
L4	58.95 ± 17.40	68.88 ± 15.97	72.02 ± 19.80	**372.89 ± 20.49**
L5	72.51 ± 19.48	83.24 ± 17.56	86.38 ± 23.19	**439.54 ± 24.23**

* Ten out of 25 measurements for iliocostalis lumborum muscle (ILC) were ignored, because the muscle had a variable attachment to the middle layer of the TLF.

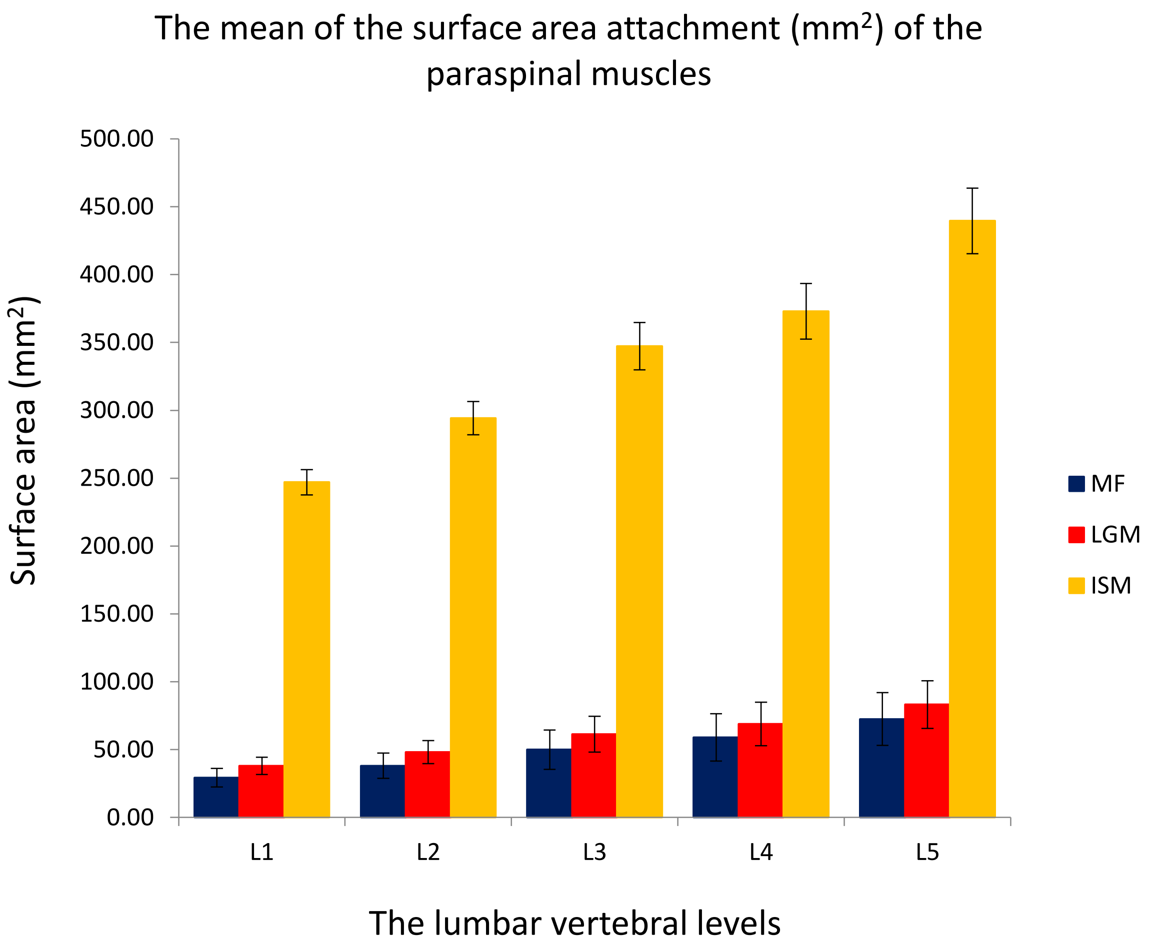

Figure 3.20 Shows the mean surface area attachments of the inter-spinalis (ISM), the longissimus (LGM) and the MF muscle in the lumbar region.

3.3.4 Cross sectional area of the multifidus muscle

The cross sectional area of the MF muscle revealed a gradual increase of the bulk of the muscle towards the inferior vertebral level. A significant difference existed between the mean cross sectional area in the specimens taken from men donors and the women's specimens, and also on both sides for both men and women ($p<0.05$; t-test). In both men and women each level was significantly different from the subjacent level below ($p<0.05$; t-test). However, the overall trend of a gradual pattern of increase of the cross sectional area when moving to the inferior lumbar levels was confirmed (Figure 3.21; Table 3.6).

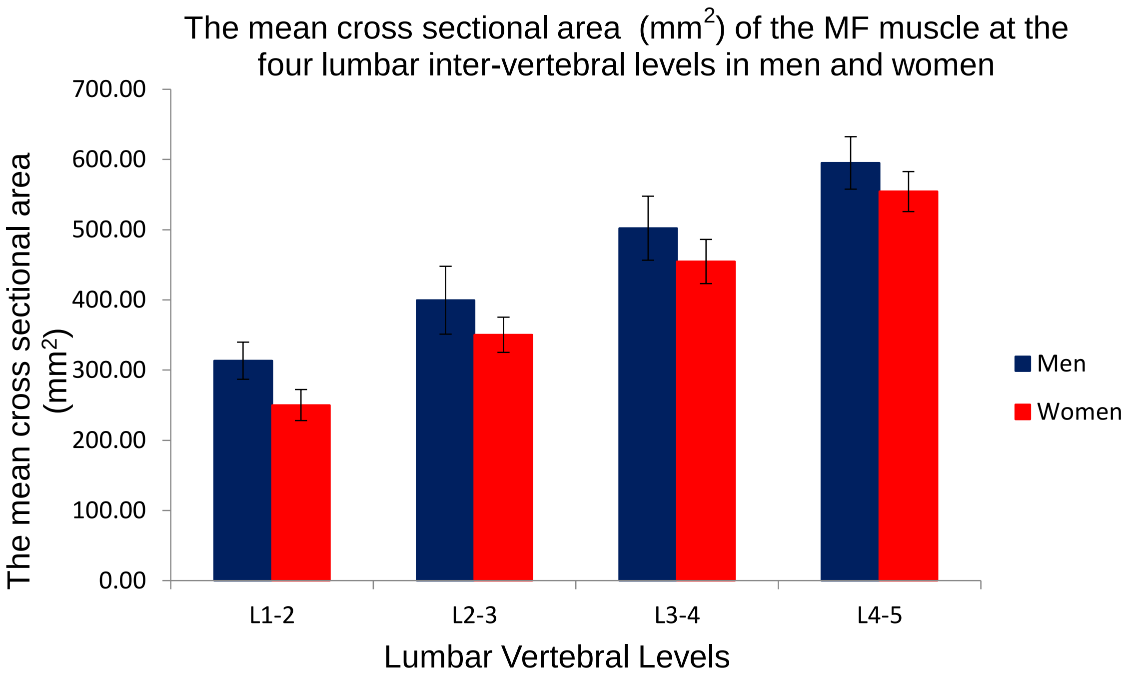

Figure 3.21 The mean cross-sectional area (mm²) of the paravertebral muscle attachments at the four inter-spinous levels.

Table 3.6 The mean cross area of the multifidus muscle at the four lumbar inter-vertebral levels in men and women.

The mean cross sectional area of the multifidus muscle in men and women at the lumbar intervertebral levels (mm²)				
Lumbar level	Men		Women	
	Mean	STDEV	Mean	STDEV
L1-2	313.50	26.39	250.13	22.14
L2-3	399.52	48.30	350.47	25.03
L3-4	501.96	45.60	454.83	31.50
L4-5	595.12	37.50	554.29	28.40

3.4 Histologic study of the lumbar muscles attachment

3.4.1 Gross observations

The variable attachment of the iliocostalis lumborum muscle was the most important gross finding. The attachment was not always directly into the tip of the transverse process; in ten specimens out of 25 (40 %) it was indirectly fused with the middle layer of the TLF (Figure 3.18B). The longissimus muscle was attached by a musculotendinous structure lateral to the superior articular process, specifically into the accessory process and the area at the root of the transverse process (Figure 3.18). Despite the variable size of this musculotendinous tendon of the longissimus muscle, the overall trend of the attachment foot print area was increased toward the inferior lumbar levels. The tendon of the MF was attached basically to the superior articular process and ascended superiorly to re-enforce the capsule FJ.

3.4.2 Histological evidence

The entheses of the iliocostalis lumborum tendon attachment to the transverse process revealed a variable degree of cartilaginous transformation. A variability in type of the entheses was also noted between the right and the left side ($p<0.05$; t-test). The enthesis of the iliocostalis lumborum tendon with the bone (transverse process) was predominantly fibrous enthesis. The enthesis type was primarily dependant on whether the attachment of the tendon into the bone was direct or indirect (Figure 3.22).

In all specimens the attachment of the iliocostalis lumborum muscle was predominantly fibrous enthesis, particularly in those where the muscle tendons were fused with the middle layer of the TLF. However, in the direct attachment of the tendon to the transverse process, some degree of fibrocartilage was observed. No considerable subcortical bone thickening or blood vessels were observed in the studied sample.

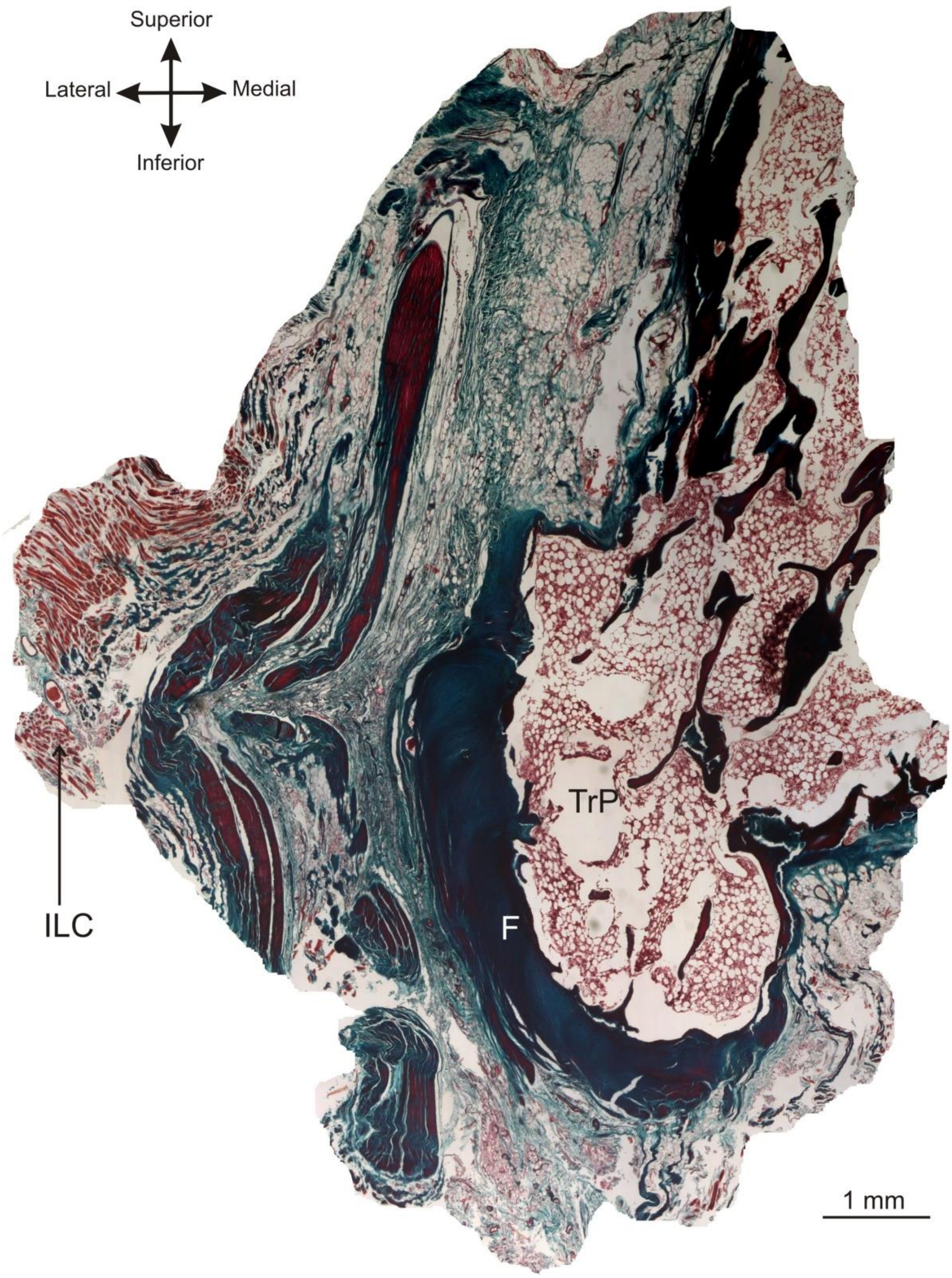

Figure 3.22 Modified Masson's staining section of the transverse process (TrP) of the left second lumbar vertebra shows the fibrous enthesis (F) which was mainly at the tip of the TrP. The iliocostalis lumborum muscle was fused with the middle layer (MLF) of the TLF just lateral to the bone (TrP).

No considerable variability was noted in the enthesis of the longissimus muscle tendon attachment with the accessory process. However, fibrocartilaginous entheses were noted in 90% of the current sample (Figure 3.23). The four typical zones of the fibrocartilaginous entheses were noted in the sections of the longissimus muscle tendon attachment with the accessory process. These zones were: pure dense fibrous connective tissue, uncalcified fibrocartilage, calcified fibrocartilage, and bone. This zone specialisation was more evident in the superior lumbar levels than in the inferior ones. Despite the attachment of the tendon of the longissimus muscle to the accessory process being composed of an attached muscular fleshy part which was (pennated) to a central tendinous part, no (direct) muscle contact to the bone or approximation was observed in any specimen. In one specimen, few blood vessels were noted which may indicate a sign of inflammation. No signs of subcortical bone thickening was observed in the slides.

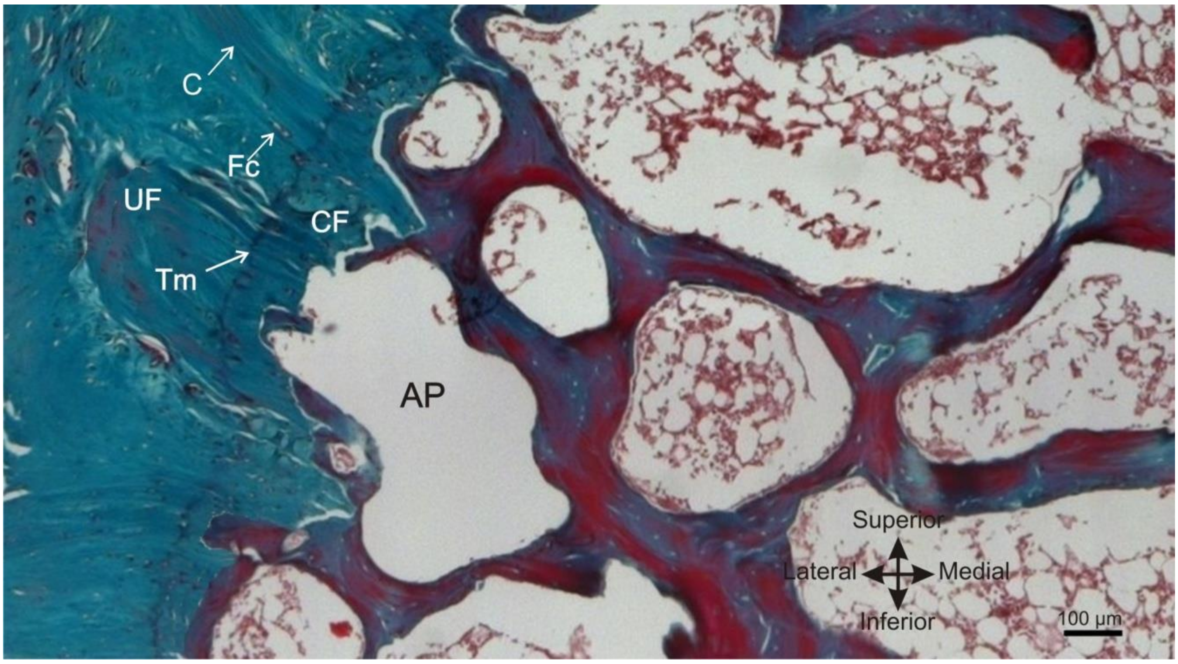

Figure 3.23 Section of the longissimus (LG) entheses with the accessory process (AP) of the left third lumbar vertebra. The fibrocartilage cells (Fc) are arranged in rows between the parallel collagen bundles (C). The enthesis was mainly fibrocartilaginous. The uncalcified fibrocartilage cartilage (UF) and the calcified fibrocartilage (CF) were separated by the tidemark layer (Tm).

The sort of attachment of the MF muscle to the tip of the spinous process was noted in all samples to be of the fibrocartilaginous enthesis type. No vascularity was observed either, and no enthesophytes (bone spur) were observed. A collection of fatty tissue was observed in five sections (20%) of the FJ blocks. In all sections the entheses were consistently extended to the capsule of the FJ. In addition, these entheses were consistent along all the lumbar levels and no level specific was observed. Subcortical bone thickenings were noted in 76% of the samples of the MF attachments to the articular process, particularly at the margins of the articular facets (Figure 3.24).

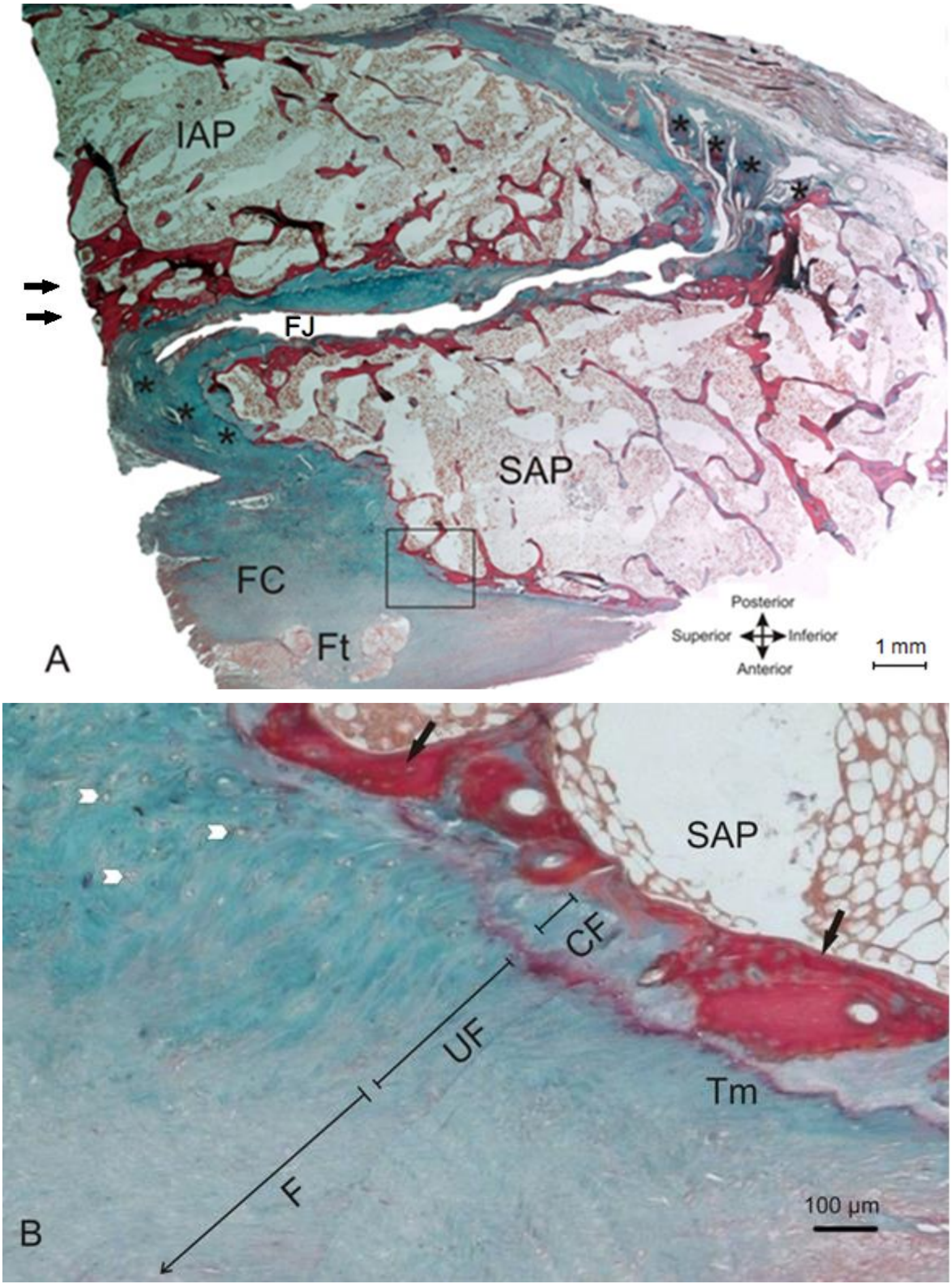

Figure 3.24 A- Modified Masson's trichrome staining section shows the fibrocartilaginous enthesis (FC) of the MF tendon into the superior articular processes (SAP). This enthesis extended to the joint capsule (*). Deposits of fatty tissue were noted (Ft). B- High magnification view of the fibrocartilage region of the MF tendon enthesis. The zone of uncalcified fibrocartilage is characterized by rows of fibrocartilage cells (white arrow heads) that are separated from each other by parallel bundles of collagen fibres. The fibrous zone (F), the uncalcified fibrocartilage (UF), the calcified fibrocartilage (CF) and the bone of (SAP) were identified. The tidemark (Tm) is relatively straight, but the tendon–bone interface is highly irregular. This is critical for the integrity of the junction (Benjamin *et al.,* 2006). The tidemark separates between the UF and the CF regions. The bone thickening was noted in 76% of the specimens in particularly at the margins of the facets (black arrows).

Chapter 4

Discussion

4.1 Three dimensional measurements of the lumbar facets

4.1.1 Gross observation

A high percentage of lumbar degenerative changes such as the vertebral body shortening, the marginal thickening and the formation of osteophytes (Figures 3.1 and 3.2) was observed. This could be explained by the fact that all the sets of the articulated lumbar vertebrae were presumed to belong to the old age group. Furthermore, the aging process and cumulative load applied lead to degenerative changes to be predominantly in the L5 vertebral body.

4.1.2 The curvature shape of the articular facet

The current findings will be compared to previous investigations which have been carried out on the importance of the facet joints in lumbar function and dysfunction. In previous research the percentage of the shape incidences were about 44% flat and 56% curved (Panjabi *et al.*, 1993; Bogduk, 2005). The current results are significantly different to these, where only 25.8% was of flat type and the C-shape (curved) was 67.8%. The previous findings were of non-specific shape pattern among the lumbar vertebral levels. This inconsistency could be attributed to several factors: first the previous study was measuring the facet joint space rather than the individual superior and the inferior articular facets, as has been done in the current study. The second point behind this difference in percentage is that most of the current sample were presumed to belong to elderly people, while in the previous study the average age of the subjects was 46.3 years (range: 19-59). In addition, it was unclear which method or definition had been adopted in the previous study to detect the shape of the facet, while the current study has a definition of deciding the shape of the curvature which was adapted to decrease the subjectivity and so to minimize the observer error.

The current study may carry an unintentional bias to a specific age group because it was carried out on a sample presumed to belong to elderly people. Therefore, it is highly recommended that future researches select samples from different age groups which, practically speaking, is not an easy design. Considering the factor of human error in detecting shape, it would be more reliable to improve an agreed definition about the shape of the curvature similar to the current one used for this study.

4.1.3 The surface area of the articular facet

Regarding the surface area of the articular facets, the greatest surface area was at the level of the L5, which could be attributed to the maximum load applied to the lower back. The lumbar facet area was significantly greater at the inferior lumbar levels. The lumbar facet surface areas measured *in vitro* in the current study were similar to the previous cadaveric studies. This age-related increment in the surface area of the articular facet was observed more in patients with history of LBP compared to asymptomatic subjects. The increase in the surface area of the facets was most probably secondary to an increased load-bearing in the lower lumbar segments and facet joint osteoarthritis (Otsuka *et al.*, 2010).

The surface area of the superior articular facets has shown a gradual increase from 144.0 mm^2 at the level of the L1 to 204.0 mm^2 at L5 level (Dahl *et al.*, 2013). The current study showed a similar pattern of increase in the facet surface area but with a smaller range from 115.0 mm^2 at the level of the L1, to 174.5 mm^2 at L5 level. This difference could be explained in the current study by the fact that the sample population is from dry bone without the covering articular cartilage. This covering cartilage might be one of the factors increasing the facet surface area in the previous study. Nevertheless, the overall trend of the gradual increment is obvious and consistent in both the current and previous findings.

A radiologic study was carried out by Barry and Livesley in 1997 had already concluded the same results which were achieved by the previous cadaveric studies. However, it excluded any significant correlation between the patient age and the measured cross-sectional area. Therefore, the best approach to studying the articular facet morphology is the three dimensional method (Dahl *et al.*, 2013). This approach allows for visualization of the entire surface of the articular facet and its curvature shape in a virtual space. Furthermore, most of the MRI studies have indirectly estimated the articular surface area by counting the thickness and multiplying it by the number of image slices. As the sample of the current investigation was from dry bone and lacked the covering cartilage, this may lead to a great difference in comparing data obtained from the three dimensional approach with image study. Therefore, it is suggested for future researches could choose different sample, for instance frozen facet surfaces of the vertebrae obtained from surgical operation or from post mortem.

4.1.4 The orientation of the articular facet

The importance of the facet orientation is still under debate in terms of the clinical relation of the facet orientation to degenerative lumbar spine diseases. A previous study could not find any association between facet orientation, facet tropism, and spondylolysis (Kalichman *et al.*, 2010). It was explained that the high percentage of osteoarthritis in those patients with spondylolysis might diminish the degree of facet sagittalisation, whereas, Boden *et al.,* (1996a) revealed that the FJ were orientated more sagittally at all levels. The greatest orientation was at the L4-5 level, where in the asymptomatic volunteers it was 41° and 60° amongst patients. The current study was done on vertebrae sets presumed to be from elderly bodies with obvious degenerative changes such as osteophytes (Figure 3.2). The current findings are consistent with the previous results of Boden *et al.,* (1996a) in relation to the association of the degree of sagittalisation with degenerative lumbar diseases. However, the sagittal angulation was most distinct at the upper lumbar levels. Another important explanation behind this relative difference is that in the previous study the angulation was measured from magnetic resonance image (MRI) sections and presented by a scheme similar to Figure 4.1. It was suggested that the best method to measure facet orientation is using the three dimensional approach (Boszczyk *et al.*, 2001).

Many previous MRI searches depend on measuring the angle by selection of two points for the coronal plane. These two points were chosen at the posterior margin of the lumbar vertebral body (Figure 4.1). In contrast the current study detected the coronal plane from a line connecting identical points on the tips of the two transverse processes, which could reduce error in the measuring process. However, both the current study and the previous MRI investigations all depend only on the anteromedial and posterolateral margins of the facet, thus neglecting the entire surface area and only measuring the angle at one plane.

It was recommended, from the results of the current analysis, to measure multiple levels within the same individual articular facet. The best way to do this is by measuring multi-level curvature of the articular facet. In those cases measuring the angulation may not have provided a real indication of its orientation, so it was better to measure the curvature of the facet radius. Thus, measuring the curvature radius may also resolve disputes regarding the definition of the facet shape.

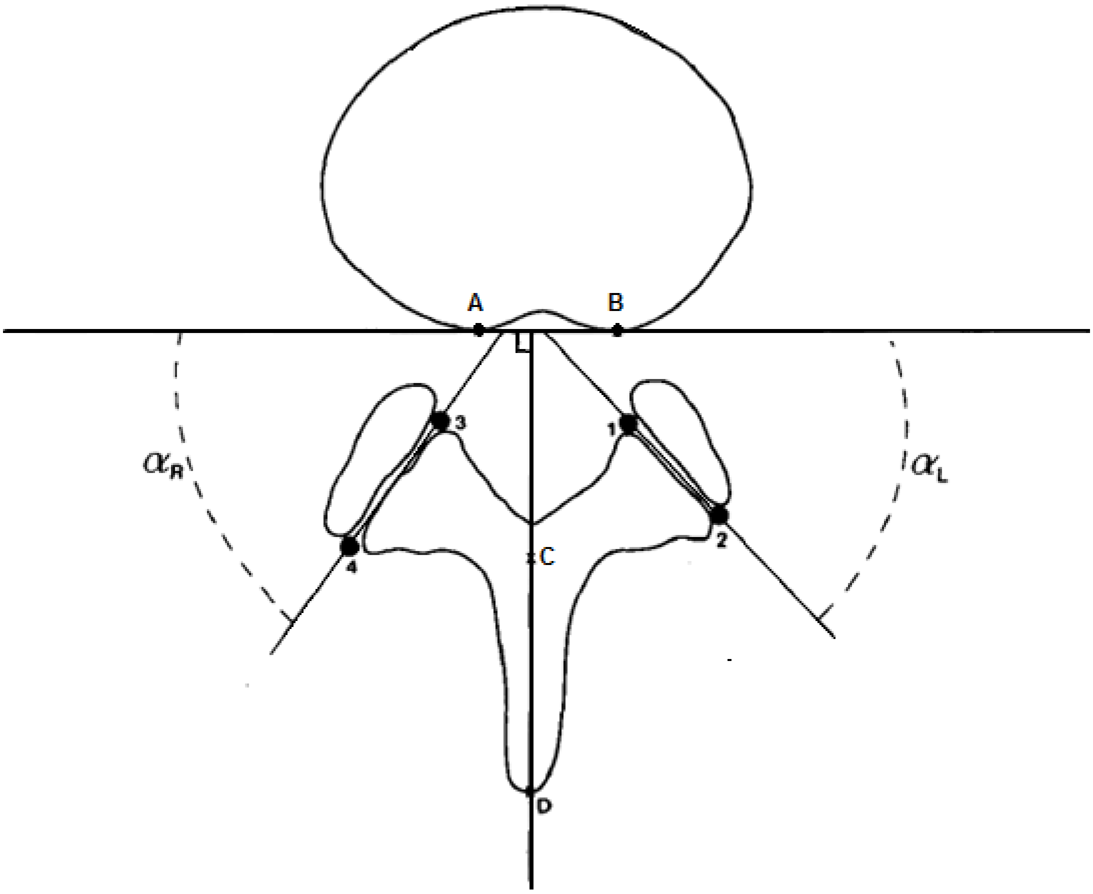

Figure 4.1 Illustration of the reference lines to measure the orientation angle (Boden *et al.*, 1996a). The points A and B were selected from the posterior margin of the vertebral body to draw the coronal plane. The points 1 and 2 represented the anteromedial and posterolateral margins of the left facet joint respectively to stand for the facet direction. Thus αL and αR can be calculated as the degree of the orientation angles of the left and right facet joints.

4.2 The superficial myofascial interactions

4.2.1 The thoracolumbar fascia

The current study quantified the three layers of the TLF. There were no argumentative issues regarding the anatomy of the layers of the TLF. The present findings were in total agreement with the previous documentation of the structure of the TLF (Tschirhart *et al.*, 2007).

Regarding the posterior layer of the TLF, the current study intensified some previous findings and disagreed with others. Most of the textbooks defined the posterior layer of the TLF as a single layer without considering it as a laminated structure. The superficial lamina of the posterior layer of the TLF was well identified to be arisen from the lower part of the latissimus dorsi muscle, however the origin of the deep lamina was less clear. The present finding disagreed with the previous description that considered the deep lamina to be derived from the aponeuroses of the anterolateral abdominal wall muscles. The inferolateral direction of the fibres of the deep lamina was completely divergent from the direction of the transversus abdominis muscle and almost profoundly at right angles from the direction of the internal oblique muscle. Probably, the deep lamina was formed from the superficial crossing fibres which extended from the aponeurosis of the latissimus dorsi muscle. The current suggestion was in accord with Tschirhart *et al.*, (2007). Parallel with this understanding was the similar direction of the superficial lamina in one side with deep lamina fibre orientation on the other. The results of the present study of the fibre decussation below the level of the L4 support such clarification. Furthermore, in some specimens, the phenomenon of fibre decussation was formed already at L2-L3 (Vleeming *et al.*, 1995). This being the case, it means that the decussation enabled the superficial fibres of one side to be continuous as deep fibres in the opposite. Mechanically this is highly acceptable as it can provide more support to a region which lacks the presence of the inter-spinous ligaments below the level of L4. However, this is in the lower lumbar vertebral level, while in the level above L4 it needs further exploration.

Moreover, it could be explained that the deep lamina was already ill-developed in the upper lumbar level (Tschirhart *et al.*, 2007). In practical terms it was difficult to follow the fibres in the decussation site due to the strong meshing of the fibres at this region. This verification may be achievable in future histologic studies. Consistent agreement about the description of composition of the posterior layer of the TLF is very important for better understanding of the biomechanical features of the posterior layer of the TLF. The present results of no gross evidence for the presence of the posterior accessory ligament between L2 and L4 was in accordance with the findings of two previous studies (Vleeming *et al.*, 1995; Bogduk and Yoganandan, 2001) and opposed the findings of Bogduk and Macintosh (1984).

4.2.2 The myofascial connections

The current study documented the superficial myofascial connections of the superficial lamina of the posterior layer of the TLF with gluteal fascia in most of the specimens. For this reason the superficial lamina showed a cross-hatched fashion at the level of L4-L5. This cross-hatch appearance was clearly lateral and inferior to the fascial decussation, and in harmony with the previous finding of Vleeming *et al.* (1995).

4.2.3 The lateral raphe and the inter-facial triangle

This study has confirmed the presence of the lumbar inter-fascial triangle clearly in 16 out of 25 specimens (64%). This current finding has proved the previous study which documented the existence of the lumbar inter-fascial triangle (Schuenke *et al.*, 2012; Willard *et al.,* 2012). The previous study noted the inter-fascial triangle in 69 out of 108 (63.9%) cadavers by axial sections. This triangle was documented to laterally mediated traction along either the middle or posterior layers of the TLF.

The lateral raphe has been observed in all specimens and this is consistent with the previous findings by Bogduk and Macintosh (1984). The existence of the lumbar inter-fascial triangle in the core potential space of the lateral raphe was confirmed. Thus the lumbar inter-fascial triangle united several fascial layers along the lateral border of the TLF, making a thick composite of dense connective tissue. In future researches, is important to investigate the biomechanical importance of the lumbar inter-fascial triangle to explore the relation between the abdominal muscles and the TLF.

4.2.4 Direction of the thoracolumbar fibres

The current result of documenting the angle of fibres using two software packages, the ImageJ and the Rhinoceros, revealed a superiority in the Rhinoceros programme. The three dimensional approach provides a better visualization of the layers of the TLF. The ImageJ measured the angle from a plane photograph which is two dimensional, therefore observer error was expected as the human back is not a totally flat surface. However, in the three dimensional reconstruction, it was very hard to control the pressure used to touch the soft tissue surface when making the landmark points by the Microscribe pointer. Therefore, reconstructing the superficial and deep layers of the posterior layer of the TLF was very challenging. Thus, measuring the fibre angle of the posterior layer of the TLF is a way to test reliability. ImageJ results are photo-based so they do not take into account the fibre angle in a third dimension (in and out of the image), while the Rhinoceros measures do take this into consideration but there is the chance of bending the fibres when touched by the Microscribe, and therefore a chance of artificially increasing the angle. Using both methods can either confirm that there is some artefact in the measures, or that they are reliable across both techniques.

One more limitation was that only a small number of samples have been reconstructed for the three dimensional model. Therefore, in the current study the significant differences between the sides, when measuring the direction of fibres using Microscribe, might not be reliable. Hence, the use of more samples is recommended for any future research, and it would be preferable to use frozen specimens.

4.3 The morphology of the lumbar para-spinal muscles

4.3.1 Gross observations

The literature reviewed contained insufficient information on the multi-bundle variation of the MF muscle. Also, pre-mortem data of the donors was not available for the current study. Handedness was noted to be the only factor associated with MF muscle asymmetry at the level of L5-S1. However, a significant MF muscle asymmetry was also reported in individuals without any symptoms of low back pain (Chaput *et al.*, 2013). It is important in future researches to investigate more about the morphology of the MF in a larger sample and with the access to the previous medical history and physical features of the donors. It is essential to investigate more about the asymmetry of the MF muscle for electromyographic (EMG) studies.

Regarding the parts of the erector spinae muscle involved in the lumbar region, many authors considered only two parts: the longissimus muscle and the iliocostalis lumborum muscle (Bustami, 1986; Kalimo *et al.*, 1989; Daggfeldt *et al.*, 2000). So, this study has adopted the same consideration by including only the longissimus muscle and the iliocostalis lumborum muscle. The spinalis thoracis (dorsi) muscle has been excluded from this study as it is entirely aponeurotic in the lumbar region (Bierry *et al.*, 2008).

The current study noted a fibrous separation between the longissimus muscle and the MF muscle in only 80% of the specimens (Figure 3.17) as compared to 100% in a previous study (Vialle *et al.*, 2005). The current study also noted an inter-muscular cleft between the longissimus muscle and the iliocostalis lumborum muscle in all specimens, in which small blood vessels and nerves were present (Figure 3.16). No clear fibrous septum was noted between the longissimus muscle and the iliocostalis lumborum muscle. The current study is very cautious about proposing the existence of a well-defined para-spinal compartment, because most of the previous findings about the presence of a para-spinal compartment were case reports and were due to traumatic or exertional factors (Songcharoen *et al.*, 1994; Paryavi *et al.*, 2010; Wik *et al.*, 2010). The current study was limited to investigating the presence of the para-spinal compartment, as it needs to be in fresh and whole body cadavers. This dispute raises the question for future plans about whether to do injection studies with latex, for instance, in order to answer this question regarding the existence of a compartment space.

4.3.2 The direction of the muscle fibres

Different rehabilitation training programmes, such as passive electrical stimulation, depend on knowledge of the internal geometry of the muscle and the force of the muscle contraction (Stark *et al.*, 2013). However, few studies investigated the external features of muscles such as the direction of its fibre in relation to surface anatomy landmarks. A previous series of two studies on seven male and female cadavers detected surface landmarks of the iliocostalis lumborum and the MF muscles (De Foa *et al.*, 1989; Biedermann *et al.*, 1991). It was concluded that there were two reference lines for EMG recordings. These lines were tested to be valid for the MF muscle at the L4-5 space and for the iliocostalis lumborum muscle at the L2-3 space. The current result aimed to prove the previous findings in a larger sample population (25 cadavers). The current results were consistent with previous findings, however the mean angle values were relatively of larger magnitude but with the same trend. In the previous study the fibre angle of the MF muscle was 15.1° and 23.5° for men and women respectively. For the iliocostalis lumborum, fibre direction was 13.0° and 12.9° in men and women respectively. In the present study the angle was measured by ImageJ programme, however in the previous work it was unclear which method was used to do the measurement. Despite the current sample population being larger than the previous study, it is highly recommended for the future plans to use an even larger sample number to ascertain a more reliable difference in fibre angulation of the MF muscle’s fibres.

4.3.3 The surface area of the attachments of the para-spinal muscles

The current study reported the variable attachments of the iliocostalis lumborum muscle especially at the L1 and L2 Levels (Figure 3.18). However, the remaining cases of iliocostalis lumborum attachment were into the lateral part of the transverse process and the posterior surface of the middle layer of the TLF. This attachment has been previously documented by many studies and is in agreement with the fascial attachment of the iliocostalis lumborum muscle to the middle layer of the TLF (Benzel, 1997; Daggfeldt *et al.*, 2000). Nevertheless, previous studies only very occasionally reported the percentage of the fascial attachment of the iliocostalis lumborum muscle. Daggfeldt (2000) mentioned that at the L2 level the iliocostalis lumborum fascicles had the largest cross-sectional area. This area accounted for almost double the mean area of the iliocostalis lumborum muscle attachments in all other lumbar levels. From the current dissection it was observed that the iliocostalis lumborum muscle had a loose attachment to the middle layer of the TLF. This raises a question about the mechanical effect of the iliocostalis lumborum in the lumbar region in those cases where the bulk of this fascicle is double the mean of all the other levels. To address part of the question, the histologic nature of the attachment of the muscle to the transverse process has been investigated and will be discussed later on.

Despite the small area of the MF's muscle attachment, its attachment to the tips of the lumbar spinous processes may enable the MF muscle to play an important role in lumbar rotational control. This finding is consistent with the previous data about the considerable atrophy of the MF muscle after a specific period of bed rest. The longissimus muscle was attached to the accessory process, just lateral to the articular process of the facet joint. Thus it was suggested that the longissimus muscle may only be involved in controlling (stabilizing) lumbar motion. The inter-spinalis muscle was bridged between the subjacent vertebral laminae, so its role is more likely to be limited to joint stabilisation.

4.3.4 Cross sectional area of the multifidus muscle

Initially the current findings give an impression that the cross sectional area of the MF muscle in all specimens had significant atrophy. This could be due to the shrinking effect of the embalming process. The reference mean of the cross sectional area of the MF muscle was generally obtained from the MRI records. However the current findings were parallel to many previous studies in view of the overall trend of the cross sectional area to be increased towards the inferior lumbar levels (Kamaz *et al.*, 2007; Hides *et al.*, 2008a; Wallwork *et al.*, 2009; Fortin and Macedo, 2013).

Previous results stated that the cross sectional area of the MF muscle at the level of L4 and L5 ranged from 3.47 cm^2 to 7.08 cm^2 for patients with chronic LBP, while the cross sectional area range for the control patient was between 4.61 cm^2 and 7.65 cm^2. When compared to the findings of previous studies, it is not clear whether this difference is or is not clinically significant. The specimens in the present work were obtained from donors who had mean age of 80 years. In this age group it was highly expected to have LBP or be disabled. The clinical importance of the MF muscle is that it acts principally as a lumbar stabilizer and controls the inter-segmental motion of the lumbar region (Solomonow *et al.*, 1998). Thus, any atrophy or injury to the MF muscle may deteriorate the spinal function. Similarly, this is the case even in the same patient when comparing the MF muscle size between the asymptomatic and the symptomatic and painful sides of patients with chronic LBP. This relationship between the symptomatic side of a patient with LBP and the size of the MF muscle can also be applied to any other para-spinal muscle (Fortin and Macedo, 2013). Nevertheless, the findings of the current study are highly suggestive of considerable MF muscle atrophy as compared to the mean of the MF cross sectional area obtained from normal subjects.

The current finding is in agreement with the cross sectional area of the MF muscle measured by the MRI in ballet dancers (Gildea *et al.*, 2013). The range of the cross sectional area in the previous study was from 200 mm^2 to 900 mm^2, while the current results, despite showing lower values (250 mm^2 to 600 mm^2), show the overall trend is the same gradual increase. The smaller size in the current work could be explained by the data having been obtained from embalmed specimens, whereas in the previous study the data was analysed by MRI for ballet dancers who were in regular activity and daily exercises.

The MF muscle atrophy, deformity or any pathological fatty infiltration retrieved by imaging modalities, whether it resulted from LBP or was a potential cause of LBP, is still under continuous debate. Therefore, future studies should be directed at answering the question of whether muscle atrophy was a cause or a result of LBP. Further studies are essential for better understanding the exact role of the MF muscle and other para-spinal muscles in the aetiology and management of common spinal diseases.

4.4 Histologic study of the lumbar muscles attachment

Regrettably, most of the studies have been carried out on the tendon’s enthesis of the limb muscles and the associated sport injuries of the tendons. Many articles focussed on the injuries of the Achilles tendon, quadriceps tendons, biceps brachii, and patellar ligaments (Kvist *et al.*, 1991), and the tibialis posterior enthesis (Moriggl *et al.*, 2003). Furthermore, the masticatory muscles enthesis was compared to the enthesis of the extremities muscles (Hems and Tillmann, 2000). Most importantly, a large volume of papers have focussed on tendon degeneration and their surgical repair (Benjamin *et al.*, 2006; Thomopoulos *et al.*, 2010; Liu *et al.*, 2011; Lu and Thomopoulos, 2013; Spalazzi *et al.*, 2013; Yang *et al.*, 2013). While, very little research so far has investigated the entheses of the lumbar para-spinal muscles.

Previous data revealed that the erector spinae (longissimus and iliocostalis lumborum) muscles had larger bulk volume (cross sectional area) in the superior vertebral levels as compared to the inferior levels (Daggfeldt *et al.*, 2000), whereas in the current findings regarding the attachment surface area of the longissimus and iliocostalis lumborum muscles, these were greater in the inferior lumbar levels than in the superior levels. It could be that when the muscles have a smaller attachment area, the translated force of contraction would be more focusing and would mechanically apply more traction to a very small limited attachment area. In other words, there is more fibrocartilaginous development in this limited area, which in turn provides more resistance against applied stress. Furthermore, there was a good correlation between distribution of the fibrocartilage within an enthesis and the applied stress, as had been noted previously (Benjamin and Ralphs, 1998). Consequently, more fibrocartilage within a tendon suggests a more 'mobile' tendon (Frowen and Benjamin, 1995). Overall, this is not the case in all lumbar para-spinal muscles.

When the iliocostalis lumborum cross sectional area was measured at the level of L2 alone, it was double the mean of the muscle cross sectional area in all the other lumbar levels (Daggfeldt *et al.*, 2000), but in the current study most of the fascial attachment of the iliocostalis lumborum was at the L1 and L2 levels (Figure 2.9). The current findings regarding the enthesis of the ILC are in a logical accordance with the fascial iliocostalis lumborum attachment. The enthesis of the tendon of the iliocostalis lumborum muscle was variable and was predominantly fibrous. This enthesis was especially encountered in those specimens where the muscle had an indirect insertion of the iliocostalis lumborum tendons to the transverse process of the L1 and L2 spines (Figure 2.9). Thereby, further investigation for the iliocostalis lumborum muscle will be very informative.

Although variability in the longissimus enthesis was present, this may be attributed to the structural manner of the musculotendinous attachment of the muscle (Bustami, 1986). However, this mixed structure of the muscle and fibrous tendon of the longissimus muscle was not observed histologically. No muscle fibres of the longissimus were viewed in the examined field near the bone or attached (directly) to the bone.

Regarding the enthesis of the MF tendon, the current result supported the assumption that MF muscle may provide the lumbar stability *via* supporting the FJ. This is in agreement with the previous belief about the function of the deep fibres of the MF muscle which were attached around the articular processes, particularly the superior articular process (Lonnemann *et al.*, 2008). Further evidence regarding the importance of the MF's supporting role to the FJ was detected in a previous study by Kong *et al.* (2009). The rotation of the FJ towards the side of the more coronal facet. Eventually this rotation could overstretch the capsular ligament of the FJ. Thus it was suggested that some degenerative changes in the FJ will be inevitable (Haig *et al.*, 2006). These degenerative changes may initiate the process of inter-vertebral disc degeneration (Kong *et al.*, 2009). Therefore, any imbalance in the applied load may affect the FJ, especially if that imbalance is persisted for a prolonged duration. In other words, the MF muscle enthesis provides support to the FJ through its capsular enthesis. Therefore, any prolonged stretching of the capsule may predispose the FJ to degeneration. To sum up, the overall view of the current finding reveals a substantial regional difference in the enthesis of the above mentioned lumbar muscles.

Fatty tissue has been noted in a small percentage of the slides (8%), as in (Figure 3.24A). The specimens belonged to donors whose age range was from 65-99 years. This fatty tissue, known as 'tendolipomatosis', was noted in the general population who were older than 35 years (Kannus and Jozsa, 1991). Generally, the presence of fatty tissue may indicate a degenerative aging change and so it may lead to spontaneous rupture within those tendons (Benjamin *et al.*, 2006).

The limitation of the current study is that no data was available about the donors and there was bias in the age group where all specimens were above 65 years. It is essential in future studies to include samples from a younger age group. Also, the degree of fibrocartilaginous formation in the enthesis needs to be analysed by a defined micro-scale so that it will be possible to differentiate different degrees of direct muscle enthesial connection, especially for the iliocostalis lumborum enthesis.

Therefore, it is highly recommended for future work to focus more on the lumbar muscles' enthesis. Economically, chronic back pain is not merely a medical issue, but is also associated with other complications such as cost of treatment, pensions and the loss of workforce and work hours (Reck, 2005). There is high incidence of rupture in the limb tendon, therefore the research is mainly directed towards the enthesis of the limb muscle (Lu and Thomopoulos, 2013). Also the prevalence of chronic LBP necessitates the need for more attention to the lumbar muscle enthesis.

Chapter 5

Conclusion

The aforementioned literature and background data demonstrated the need for a detailed quantitative model of the lumbar musculoskeletal structures that provide and support core mobility and stability. This understanding is essential for better evaluation of the role of each structure. A detailed anatomical knowledge about the quantitative morphology of the lumbar vertebrae in relation to core stability will enable more precise testing and understanding of normal back function and dysfunction in a variety of common low back disorders. These outcomes could re-emphasise the current concept and clarify disputes regarding spinal stability and LBP among the medical and physiotherapy practices.

5.1 Three dimensional modelling of the lumbar facets

Most of the lumbar spines of the sample population showed different grades of degenerative features. The marginal thickening and decreased height of the vertebral body was marked in the fifth lumbar vertebra. Osteophyte formation was observed in considerable proportions. These degenerative changes were more evident in the articular facets in terms of the peripheral thickening and, to a lesser extent, the formation of osteophytes. Presumably, these degenerative changes indicated aging processes that affect the lumbar spines.

The curvature shape of the FJ can be categorised into two main types: curved (C) and flat shapes. A further minority of the facets were outlined as J shape. The highest percentage of the curved C-shape was at the first lumbar spine. Therefore, in clinical findings the degeneration was more at L4-L5 and L5-S1 levels. The C-shape provides more resistance to anterior displacement of the vertebra than the J shape and flat shape in the superior lumbar levels, while most of the flat shape was found to be in the inferior facets at the L4 spine.

The mean articular surface area showed a gradient increase towards the L5 spine. Hence the greatest surface area was at L5 and the least at L1. Practically, this implies the increased load is applied to the lower lumbar spines, which in turn puts these spines at risk of different degenerative diseases.

The facet orientation is of important clinical value in assessment of patients with LBP. The degree of sagittalisation was more in the upper lumbar level and gradually decreased towards the lower levels. The results suggest a clear correlation between the sagittal direction of the facet joints and the degenerative process. These data have an important clinical implication and may permit prediction of FJ at higher risk of degeneration joint diseases. Coronally oriented facets are more resistant to anterior dislodgement of the vertebral body. These findings are crucial in evaluation of degenerative disorders like spondylolisthesis. However, the articular facets have different shapes. In such cases, measuring the angulation may not provide a real indication of facet orientation. Therefore, it is recommended that future studies measure the radius of the facet curvature which may provide more knowledge regarding one of the current debates about the myth of core stability.

5.2 The superficial myofascial interactions

Lumbar soft tissues are vital components in spinal stability. The posterior layer of the TLF was clearly identified with its two sub-layers: the superficial and deep laminae. The thickening of the TLF at the midline from the L2 to the L4 levels was noted. Decussation of the fibres of the superficial lamina below the L4 level was documented and suggested provision of more support at this level where there are no spinal ligaments.

There were numerous myofascial connections between lumbar and gluteal regions, both through muscular and connective tissues. This implies an important channel for translating load between the upper limbs and the lower limbs via the TLF. In addition, these myofascial connections may provide more integrated stability to the thoracolumbar and lumbosacral regions. Decussation of the fibres of the posterior layer of the TLF below the L4 level was suggested to provide more support at this level where there are no spinal ligaments. Many connections between lumbar and gluteal regions, both via muscular and connective tissues, were noted. These connections provide important channels for translating load between the upper limbs and the lower limbs via the TLF. In addition these myofascial connections may provide more integrated stability to the thoracolumbar and lumbosacral regions.

Similarly, the lateral raphe and the lumbar inter-fascial triangle represent a converging fascial balance between the anterolateral abdominal muscles and the thoracolumbar muscles and fascia. These lateral fascial connections may mediate the force translation that is created by the intra-abdominal pressure to the TLF. The observations mentioned in this study suggest stronger muscular and connective tissue connections between lumbar and gluteal structures. This reinforces the long-held suspicions of many allied health practitioners. This suggests that further emphasis on the preventative and the rehabilitative programmes that link these areas should be encouraged.

The angle of direction of the superficial and deep laminae of the TLF was measured by both planar method, using ImageJ software (Rasband, 1997-2014) and the three dimensional model. Three dimensional design allows direct visualization of the multiple layers of the TLF, which is impossible by other methods.

This study could not certify the presence of a lumbar para-spinal muscular compartment. Physiological studies and/or injection with resins should adopted to investigate the existence of a lumbar para-spinal compartment space.

5.3 The morphology of the lumbar para-spinal muscles

The morphology of the para-spinal muscles was investigated for better understanding of the supporting function of the MF, iliocostalis lumborum and longissimus muscles. These muscles were variable in terms of the fibre arrangement and attachment area. The MF fibres were arranged in two varieties: the uni-bundle pattern (common) and the multi-bundle pattern (uncommon). The longissimus muscle was inserted by a musculotendinous tendon of variable attachment area among the specimens of the study, while the iliocostalis lumborum muscle showed great inconsistency in its attachment into the transverse process of the lumbar spines.

Inter-muscular clefts were clearly identified between the iliocostalis lumborum and longissimus muscles. No fascial lamina was noted in the cleft but the neurovascular structures were found in all specimens. The second cleft was noted between the MF and the longissimus muscles. Variable amounts of fatty infiltration into the MF muscle was noted, which may suggest an aging atrophy of the muscle.

The attachment surface area of the three mentioned muscles and the inter-spinalis muscle revealed a pattern of increase pattern downwards to the L5 level. The attachment of the MF muscle to the FJ capsule was documented. The MF and the inter-spinalis muscles were suggested to be more stabilizers, while the iliocostalis lumborum and longissimus muscles were considered to be more movement-generating. The overall diminished cross sectional area of the MF muscle suggests muscular atrophy in this sample of specimens from elderly donors.

The orientation of the iliocostalis lumborum fascicles were parallel to each other and extended downward parallel to a reference line defined between the posterior superior iliac spine and the intersection of the lateral border of the iliocostalis lumborum muscle at the 12th rib. Similarly, the MF muscle fibres were noted to be parallel to their reference line which was defined between the posterior superior iliac spine and the L2-L3 inter-spinous space. These reference landmarks may provide important landmarks for electromyography recordings to detect the optimum site for measuring the activity of the MF and iliocostalis lumborum muscles in a given training task. These results could have clinical implications for the management of patients who are suffering from chronic back pain. Future plans need to be encouraged for the calculation of fibre angle in younger age groups.

5.4 The histological findings

The enthesis of the lumbar muscle has received relatively little attention from researchers and tissue engineers as compared to the limb muscles. The histological attachment of the lumbar para-spinal muscles was documented. These attachments were correlated to the gross observations of the muscle attachment area that has been already noted. The two types of enthesis (fibrous and fibrocartilaginous) were observed and documented for the MF, longissimus and the iliocostalis lumborum muscles.

The iliocostalis lumborum enthesis was mainly of a fibrous type. Indirect insertion of the iliocostalis lumborum muscle was clearly noted. The longissimus muscle attached via a musculotendinous tendon into the accessory process of the lumbar vertebrae. The LG enthesis was predominantly fibrocartilaginous. Similarly, the attachment of the MF tendons to the spinous process and the articular processes of the FJ were fibrocartilaginous. The enthesial attachment of the MF extended to the capsule of the FJ. This suggests that the MF muscle enthesis provides support to the FJ through the capsular enthesis. Contrarily, prolonged stretching of the capsule may predispose to FJ degeneration. This knowledge about the lumbar enthesis will promote better understanding of the regional lumbar enthesis which may carry positive clinical implications when dealing with rupture injuries or in the management of unexplained LBP.

Future studies should be focused more on the ultra-structure of the tendon enthesis for the lumbar para-spinal muscles. The study of the mineral composition of the enthesis would highlight the mechanical properties of the enthesis. This micro-anatomical knowledge may decrease the failure rates in surgical repair of injured tendons and might make a substantial advance in tissue engineering.

Chapter 6

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Appendices

Appendix I

The Embalming Process of the Laboratory of Human Anatomy

All cadaveric specimens used in this study were from the Laboratory of Human Anatomy, College of Medical, Veterinary and Life Sciences, School of Life Sciences, University of Glasgow. The specimens were embalmed using the standard procedure.

For a 20L mix:

55% ethanol (100% undenatured)

5% formalin (40w/v)

5% phenol (88% aqueous)

20% propylene glycol

15% hot water

This mix is introduced to the cadaver via a cannulated common carotid artery with the mix suspended at ceiling height to generate a pressure of approximately 12psi.

The cadaver is then stored at four degrees celsius for a minimum of three months in order to allow the water content of the specimen to evaporate under the influence of the fixative.

This embalming protocol ensures that the specimen is available for long term usage, with only slight discolouration, no fungal growth, low levels of airborne toxins and excellent flexibility and tissue differentiation. The specimens are also suitable for histological investigation as the cellular content of most tissues remains undisturbed. This embalming procedure was therefore appropriate for this study and facilitated the multi-discipline approach to the investigation.

Appendix II

Processing of Histological Specimens

i- Decalcification

The specimens selected for histologic examination were first decalcified in:

1% EDTA
9.5% nitric acid (HNO_3)
distilled H_2O

Each specimen was placed in a container decalcifying solution of a volume approximately four times that of the specimen. The container was then sealed and placed on an agitator to stir the solution. The agitation was a vital component of the process, as this maximised the usage of the solution by exposing all of the solution to the specimen.

Consequently, the process was accelerated by the change in solution and the change in procedure. The decalcifying solution was changed either daily or when the solution turned deep yellow in colour (indicating saturation of the solution with calcium), whichever came first. This regime was accelerated to once every two days, as total decalcifying time dropped below two weeks. The majority of specimens were ready for the next stage of processing within three to five days.

ii- Double-Embedding

A double-embedding procedure was utilised after Fogg (2004), the procedure was as follows:

50% alcohol all day
70% alcohol overnight
95% alcohol all day
absolute alcohol 1.5 hours, then change for overnight
50% alcohol:50% diethyl-ether half day
1% cellulose nitrate in

50% alcohol:50% diethyl-ether half day, overnight, half day
chloroform 30 minutes.
dry on paper
immerse in liquid paraffin wax 20 minutes
vacuum to 15Pa in liquid paraffin wax 30 minutes
vacuum to 20-25Pa in liquid paraffin wax 2 x 1.5 hours

The addition of diethyl-ether and cellulose nitrate, and the reduction of chloroform exposure greatly improved the quality of the specimens.

iii- Moulds and Block Orientation

The processed specimens were embedded in paraffin wax. A small was fixed to the block as a landmark for positioning later on. Different size of metal moulds were used according to the required size of the blocks. For further documentation the blocks were photo as reference for positioning. The orientation of the block was predetermined such that they desired cutting surface was exposed and could be placed face-down in the mould. Liquid paraffin was then poured around the block and allowed to set.

Appendix III

Rotatory Microtome Sections

All of the histologic sections used in this study were cut using a Rotatory Microtome in the Laboratory of Human Anatomy, the University of Glasgow.

i. Thickness Selection

The specimens were to be cut as thin as possible to permit the clearest examination of the tissues as possible. Suitable sections were cut as small as 6μm, but this was not consistently achievable. The section thickness varied between blocks, but most were done at 8μm. It may be suggested that the bones within these specimens were either of poor quality before death, or were unable to withstand the intensive embedding procedure.

ii. Dealing with Variable Outcomes from Processing

Several techniques were used to ensure optimal sectioning of the tissue and to accommodate difficulties in particular blocks or in particular regions of a block. Prior to cutting each block was placed on a cold plate to get the block as cold as possible. This was found to improve the initial cutting/trimming of the block as the superficial wax held together better when cold. Once the full surface of the block was being cut and sections were ready to be selected, the block was moistened with warm water and allowed to penetrate the wax. This facilitated smooth cutting of the block and assisted in keeping the section together as it was raised across the blade. This may also have softened the specimen slightly, facilitating smooth drawing of the blade through the specimen, essential for suitable sections. If the sections still continued to fall apart, or the block was cutting poorly, a solution of 1% cellulose nitrate in alcohol was painted across the block surface and left to form a gel. This coating penetrated the block and held subsequent sections together. These techniques were repeated as necessary throughout each block to ensure section quality.

The slides were used were already have an adhesive face to facilitate. Otherwise if plain slides were used, then each slide was coated with a gelatine mixture.

Solution

2.5g gelatin

0.25g chromium III potassium sulphate ($CrK(SO_4)_2\ 12H_2O$)

500mL distilled water

Gelatin dissolved into 250mL distilled water on medium heat with stirrer

Chromium dissolved in 250mL of distilled water

Gelatin solution added to chromium solution through filter paper.

Procedure

Slides were cleaned with soapy water

Rinsed in warm water Placed in warm gelatin solution and carefully removed to avoid creating bubbles on the slide surface.

Placed in oven (50^0C) overnight

Sealed in airtight container until used.

Appendix IV

Modified Masson’s Trichrome Staining

Ingredients

Mayer’s haematoxylin

Ponceau de xylidine

Phosphomolybdic acid

Acid fuchsin

Glacial acetic acidLight green SF

Hydrochloric acid

Stains

1. Cytoplasmic Red

A = 1% ponceau de xylidine in 1% acetic acid

B = 1% acid fuchsin in 1% acetic acid

Mix together in a ration of 2A:1B

To make 300mL

A = 2g ponceau de xylidine + 2mL acetic acid in 200ml H_2O

B = 1g acid fuchsin + 1mL acetic acid in 100mL H_2O

The final pH ≈ 3.05

2. Light Green

2g Light Green SF + 2mL acetic acid + 100mL H_2O

Final pH ≈ 2.85

Procedure

Bring sections to water

Stain in Mayer’s Haematoxylin (A +B) for 5 minutes

Rinse in tap water

Differentiate in 1% HCl (2-3 quick dips)

Rinse in tap water

Blue in running tap water for approx. 10 minutes

Check that only nuclei are stained
Stain in Cytoplasmic Red for 1 minute
Rinse in two washes (dips) of 1% acetic acid
Displace in 4% phosphomolybdic acid for 2 minutes
Rinse in 1 wash of 1% acetic acid
Stain with Light Green for 35-70 seconds (may have to vary time)
Rinse in 1 wash of 1% acetic acid
Blot, dehydrate, clear and mount with Pix mounting media

This procedure was modified from the standard Masson's trichrome procedure by replacing an ammonia water wash with gently running tap water for ten minutes (finer control over "bluing" of sections). The red and green staining times were also reduced, particularly the green staining time, to enable finer control over the strain. Staining times of the original procedure resulted in heavy staining of all structures and subsequent loss of detail within each section.

Appendix V

Digital Photography

i. The camera

All the photos in this thesis were taken using the Canon camera (EOS, 40D) digital cameras. All photos were taken at the highest resolution, utilising the 10.1 megapixel of the camera. All photos were taken with the camera in “manual” mode, allowing complete control over shutter speed, aperture, white balance, focus et cetera. The camera was stabilised with the aid a boom-arm tripod, enabling the camera to “hang” over the specimen from short distances and in different angles. This facilitated the capture of “close up” macroscopic photographs, highlighting fine details of the specimens.

ii. The Lights

All of the photos were taken with the aid of artificial lighting. Usually two standard studio lights were used to highlight specific structures on the specimens and to ensure that the specimens were properly aligned for digital measurement. The latter was achieved by positioning each light separately to yield consistent shadow on the opposite side of the specimen or of a particular structure within the specimen. Even shadow from either light ensured that select structures would be in the same plane when photographed, and hence could be measured with the same scale.

iii. Photo Formats

The photos were taken at the highest resolution possible with each camera. It was determined that there was no significant difference between high resolution compressed JPEG images and uncompressed TIFF images. Once downloaded from the camera, the images were saved as TIFF files to ensure resolution wasn’t lost after saving edited versions of the files. The detail achievable was sufficient for A4 prints of the photos to be produced with no apparent loss of quality.

Appendix VI

Digital Measurements with Image J

i. Image J

The “shareware” program Image J (Rasband, 1997-2014)[1] was used for all digital measurements. The program enabled lengths, areas, perimeters and angles (amongst many other things) to be measured on the digital images captured of each specimen. Accuracy of measurements may have been enhanced in this way, as the images were often magnified to several times their actual size enabling landmarks to be more clearly demarcated.

ii. Scale setting

The Image J program facilitated scale setting for each specimen. An initial measurement in pixels of a known distance was used to determine the scale of the image. All remaining measurements were translated into the correct scale and recorded automatically in Microsoft Excel.

iii. Digital Measurements

All measurements were made by dragging the cursor from one point to another, around a structure, or between several points. Selection of particular tools (length, area, and angle) from the program’s menu determined the measurement to be made. Accuracy of the selection could be checked by changing magnification of the image and then accepted or adjusted and re-measured.

1

[1] Rasband, W. S. 1997-2014. Imagej. U.S. Nitional institutes of health, Bethesda, Maryland, USA, http://imagej.Nih.Gov/ij/.

Appendix VII

Reconstruction technique

The lumbar spine was fixed to the stage. After the Microscribe device has been loaded. Three point were taken around the spine to calibrate the three x, y and z axes. The principle of the reconstruction by the Microscribe is illustrated in the figure A.1. Multiple points were taken along the facet surface so the coordinates were saved in the software and by pressing entre the points will be connected to form the first curve (step 1 and 2). The process will be repeated as much as parallel curved are required to cover the whole articular surface of the facet. The curves must not intersect with each other (step).

The Rhinoceros software has the facility to loaf multiple curves into one three dimensional model surface (step 4). Another option can render the loafed surface to the required view (step5). Eventually, many properties of the programme enable to measure the length of fibre (curve), the surface area of the facet, the angle of orientation and so on.

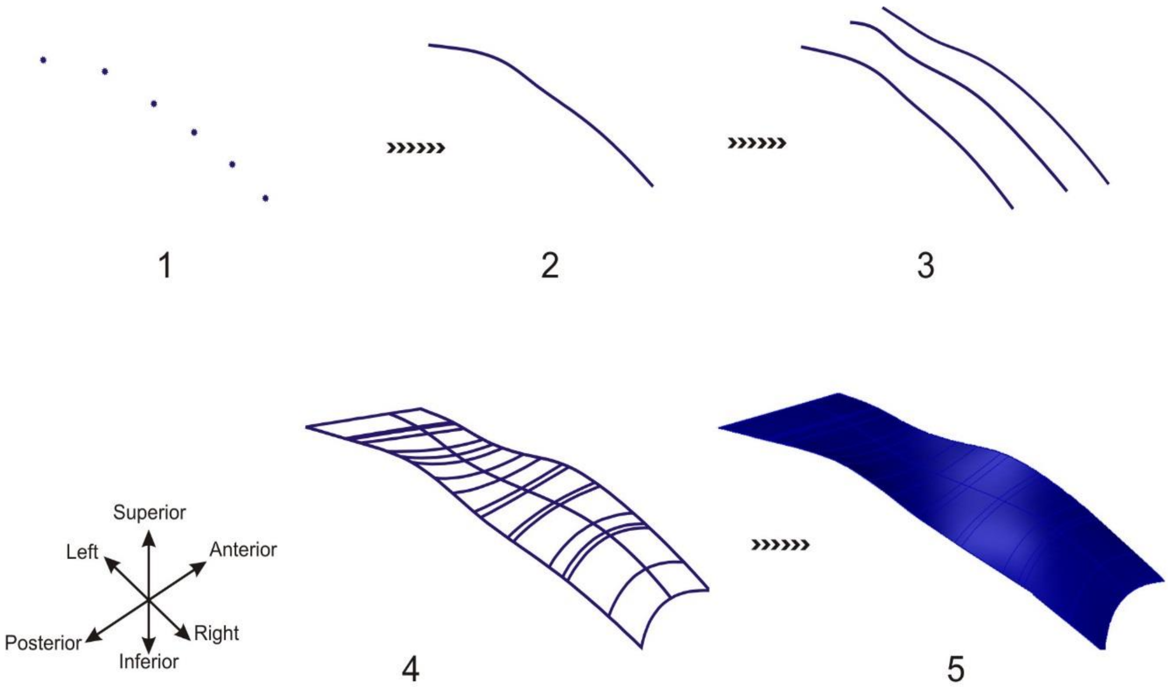

Figure A. 1 Illustrate the steps of reconstructing a surface into three dimensional model: 1- More than two at least need to be created in the virtual space in order to make a curve. 2- Thus one curve has been created. 3- This will be repeated until mapping all the object surface. 4- The group of selected curves will be as one surface by pressing loaf order. 5- The final geometric model now is completed.