



# Sarcomere length organization as a design for cooperative function amongst all lumbar spine muscles



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## ABSTRACT

The functional design of spine muscles in part dictates their role in moving, loading, and stabilizing the lumbar spine. There have been numerous studies that have examined the isolated properties of these individual muscles. Understanding how these muscles interact and work together, necessary for the prediction of muscle function, spine loading, and stability, is lacking. The objective of this study was to measure sarcomere lengths of lumbar muscles in a neutral cadaveric position and predict the sarcomere operating ranges of these muscles throughout full ranges of spine movements. Sarcomere lengths of seven lumbar muscles in each of seven cadaveric donors were measured using laser diffraction. Using published anatomical coordinate data, superior muscle attachment sites were rotated about each intervertebral joint and the total change in muscle length was used to predict sarcomere length operating ranges. The extensor muscles had short sarcomere lengths in a neutral spine posture and there were no statistically significant differences between extensor muscles. The quadratus lumborum was the only muscle with sarcomere lengths that were optimal for force production in a neutral spine position, and the psoas muscles had the longest lengths in this position. During modeled flexion the extensor, quadratus lumborum, and intertransversarii muscles lengthened so that all muscles operated in the approximate same location on the descending limb of the force-length relationship. The intrinsic properties of lumbar muscles are designed to complement each other. The extensor muscles are all designed to produce maximum force in a mid-flexed posture, and all muscles are designed to operate at similar locations of the force-length relationship at full spine flexion.

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## 1. Introduction

The spine is a highly complex structure, consisting of multiple intervertebral joints capable of multi-degree of freedom movement. Due to this complexity, its control is regulated by a vast array of seemingly uniquely designed muscles. How these muscles generate force determines spine movement, loading, and stability; thus, it is important to understand how all the muscles function and interact as a complete system. The use of electromyography has been critical in determining how the spine muscles are activated and load the spine under a variety of conditions (e.g. Marras and Granata, 1997; Larivière et al., 2003; Kavcic et al., 2004; Dufour et al., 2013). However, knowledge of the fundamental structural design of these muscles, a powerful determiner of function, is lacking and requires further study.

The design of muscles, including their architectural and intrinsic properties, provide the basic template for force production and is one of the best predictors of the muscle function (Lieber and Fridén, 2000). The sarcomere is the fundamental unit of muscle force production, and sarcomeres can be organized in many different

patterns to create various physiological cross-sectional areas (PCSA) and fiber/muscle lengths, which provide some sub-specialization for generating greater force or wider excursions, respectively. There has often been a trend of studying individual spine muscles in isolation, and then attributing isolated roles and functions to these muscles. Multifidus has been often implicated as the most important of the spinal muscles (Danneels et al., 2002; Wilke et al., 1995). However, others have argued that, while aspects of multifidus structure or function may be unique, it is essential to consider all muscles in concert, and necessary for all these muscles to work together to create an appropriately controlled and capable system (McGill et al., 2003; Wagner et al., 2005). Interestingly, multifidus has recently been predicted to act exclusively on the ascending limb of the sarcomere force-length relationship, reaching optimal length in full spine flexion; however, in this study multifidus was the only muscle considered (Ward et al., 2009). McGill and Norman (1986) previously predicted that all lumbar extensor muscles would share this same trait. Thus, we were motivated to assess sarcomere organization in a wider array of spine muscles.

Sarcomere length is an important intrinsic property of muscle force production as it affects binding of myosin head groups to actin filaments. The muscle force-length relationship describes the maximal capability of forming cross-bridges at different fiber, and their

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constituent sarcomere, lengths (Gordon et al., 1966). Whole muscles each have unique force-length relationships depending on architectural parameters such as fiber length, which is determined by the number of sarcomeres in series, and tendon length (Zajac, 1989); however at the level of the sarcomere there is a single unique force-length relationship for human skeletal muscle, which consists of an ascending limb, plateau region, and descending limb (Walker and Schrodt, 1974; Gollapudi and Lin, 2009). The plateau region of this relationship, at lengths between  $\sim 2.6$  and  $2.8 \mu\text{m}$  in human skeletal muscle, is optimal for force production; it is this length at which a maximum number of myosin head groups can form cross-bridges with actin. Sarcomere length operating range is a function of each of muscle length, fiber length, and the geometric orientation of the muscle (moment arm) with respect to the joint(s) that it crosses. This operating range can be considered the range each sarcomere will shorten or lengthen through normal joint motion. By having short sarcomere lengths in a neutral posture and a narrow operating range in spine flexion, multifidus force production is inherently limited in a neutral spine position and can only produce maximal isometric force when the spine is in full flexion (Ward et al., 2009). On the contrary, psoas major has long sarcomeres in a neutral spine position and approaches optimal lengths during full hip flexion (Regev et al., 2011). The effect of lumbar spine position on sarcomere length operating ranges of psoas major and the remaining lumbar muscles are unknown.

The purposes of this study were to: (1) measure neutral cadaveric sarcomere lengths of the muscles that surround the lumbar spine; and (2) model the sarcomere length operating range through full lumbar spine flexion, extension, lateral bending, and axial rotation. As multifidus and psoas major lie posterior and anterior to the spine, respectively, the lumbar extensor (posterior) muscles were hypothesized to operate on the ascending limb of the force-length relationship, similar to multifidus, while muscles located more anteriorly would have operating ranges more similar to psoas major on the descending limb.

## 2. Materials and methods

### 2.1. Cadaveric donors

Muscle sarcomere lengths were measured from one side of the body of seven cadaveric donors (6 male, 1 female, aged  $77 \pm 8.5$  years). All donors were

embalmed in an approximately neutral anatomical posture and had no visible musculoskeletal or spine-related injuries. The embalmed nature of the muscles is necessary for the type of architectural measurements made in this study (Lieber and Fridén, 2000). The Research Ethics Board at the university approved the use of the cadavers for this study.

Surrounding tissues were carefully dissected to expose the muscle fascicles, tendons, and bony insertions of the lumbar spine muscles. Samples approximately 10–12 fascicles thick and 0.5 cm long were excised from muscles of interest (Table 1) and stored in phosphate-buffered saline solution. After sampling, the remaining musculature was removed to expose deeper tissues. A posterior approach was used to sample iliocostalis, longissimus, multifidus, and intertransversarii, while the psoas muscles and quadratus lumborum were accessed anteriorly. Psoas minor was absent in four of the seven donors, resulting in three psoas minor muscles examined. Intertransversarii muscles from one donor were not fully embalmed and were removed from analysis, resulting in intertransversarii muscles of six donors being examined.

### 2.2. Sarcomere length measurement

Laser diffraction, as described by Lieber et al. (1990), was used to measure muscle sarcomere lengths. Specifically, a 5 mW diode laser (wavelength=635 nm; beam diameter  $\approx 1.4$  mm) was shone through the muscle samples and the resulting diffraction patterns were recorded by a 256 element linear photodiode array and digitally converted. The resulting diffraction patterns were projected on the computer screen, and a custom LabView program was used to measure the calibrated distance between 1st order to 1st order peaks. Sarcomere lengths of three to six different fascicles were measured for each muscle sample. Each sarcomere length measurement yields an average value from thousands of individual sarcomeres that fall within the diameter of the laser beam on the muscle fascicle.

### 2.3. Modeled operating ranges

Operating ranges of lumbar spine muscles were modeled using anatomically detailed geometric coordinate data, representing a 50th percentile male, from the model of Cholewicki and McGill (1996). Muscles were modeled as lines of action connecting skeletal attachment sites (e.g. specific bony locations, representing muscle origin and insertions, on the pelvis and spine; the erector spinae line of action also included a nodal point to account for curvature along the spine) using a custom MATLAB 7.0 program (MathWorks, Natick MA) (Fig. 1). The superior muscle attachments were rotated sequentially about each intervertebral joint from L5/sacrum to L1/L2, accounting for differences in range of motion of each level, throughout the population average full range of lumbar flexion, extension, and both lateral bend and axial rotation ipsilaterally and contralaterally (Table 2; White and Panjabi, 1990; McGill, 2007). Therefore, rotated muscle attachments are dependent on the number of intervertebral joints crossed, the distance from the joint center, and the magnitude of rotation at each joint. The total lengths of each vector, representing individual muscle fascicles, were calculated in both neutral and rotated positions. The percent change ( $(\text{rotated length} - \text{neutral length})/\text{neutral}$

**Table 1**

Location and attachment sites of all muscle fascicles that were sampled. Samples were taken in the approximate mid-belly of the muscle between attachment sites.

Muscle	Location	Inferior attachment	Superior attachment
Iliocostalis <sup>†</sup>	Thoracic Lumbar	Iliac crest via ESA Iliac crest	Angle of rib 8 L1 transverse process
Longissimus <sup>†</sup>	Thoracic Lumbar	Iliac crest via ESA Iliac crest	Angle of rib 4 L1 transverse process
Multifidus	L1 L4	Posterior superior iliac spine Sacrum	L1 spinous process L4 spinous process
Intertransversarii	Medialis Lateralis	L2-L5 mammillary processes L2-L5 transverse processes	L1-L4 accessory processes L1-L4 transverse processes
Psoas major	L1 L4	Pectineal line of pelvis Lesser trochanter of femur	L1 vertebral body L4 vertebral body
Psoas minor	L1	Pectineal line of pelvis	L1 vertebral body
Quadratus lumborum		Iliac crest	Rib 12

ESA: erector spinae aponeurosis.

<sup>†</sup> In the lumbar region, the intramuscular septum was used to divide iliocostalis and longissimus (Bogduk, 1980). Thoracic and lumbar samples all arose from the iliac crest directly or indirectly via the ESA. Thoracic level iliocostalis samples were therefore taken from iliocostalis lumborum rather than iliocostalis dorsi (Gray, 1985).

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