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Curved muscles in biomechanical models of the spine: a systematic literature review

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ABSTRACT
Early biomechanical spine models represented the trunk muscles as straight-line approximations. Later models have endeavored to accurately represent muscle curvature around the torso. However, only a few studies have systematically examined various techniques and the logic underlying curved muscle models. The objective of this review was to systematically categorize curved muscle representation techniques and compare the underlying logic in biomechanical models of the spine. Thirty-five studies met our selection criteria. The most common technique of curved muscle path was the 'via-point' method. Curved muscle geometry was commonly developed from MRI/CT database and cadaveric dissections, and optimization/inverse dynamics models were typically used to estimate muscle forces. Several models have attempted to validate their results by comparing their approach with previous studies, but it could not validate of specific tasks. For future needs, personalized muscle geometry, and person- or task-specific validation of curved muscle models would be necessary to improve model fidelity.

Practitioner Summary: The logic underlying the curved muscle representations in spine models is still poorly understood. This literature review systematically categorized different approaches and evaluated their underlying logic. The findings could direct future development of curved muscle models to have a better understanding of the biomechanical causal pathways of spine disorders.

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KEYWORDS
Curved muscle; wrapping muscle; muscle path; spine model; biomechanical model

1. Introduction

The trunk muscles are the primary generators of force within the spine during both static and dynamic exertions (Chaffin 1969; Schultz and Andersson 1981; Mcgill and Norman 1986; Marras and Sommerich 1991; van Dieën and Kingma 2005; Arjmand et al. 2010; Gagnon et al. 2011). Additionally, the direction or 'path' of the muscles plays an important role in defining loads and moments imposed on the spinal units and discs since changes in muscle length, muscle velocity, muscle moment arms and muscle force lines of action are important contributors to force generation (Garner and Pandy 2000). Historically, the torso's muscle lines of action have been represented by straight-line force vectors defined by connecting the anatomical origin and insertion of the muscles (Chaffin 1969; Schultz and Andersson 1981; Mcgill and Norman 1986; Marras and Sommerich 1991; Granata and Marras 1993). While straight-line muscle representations are relatively easy to implement within a model and are reasonable approximations for some exertions, these representations could become problematic for more complex or extreme exertions where straight-line muscle representations may not align well with anatomical structures (Garner and Pandy 2000; Arjmand, Shirazi-Adl, and Bazrgari 2006).

In order to overcome this issue, curved muscle lines of action have been suggested to represent more accurate muscle mechanics during complex or extreme exertions (Delp et al. 1990; Santaguida and McGill 1995; Garner and Pandy 2000; Arjmand, Shirazi-Adl, and Bazrgari 2006; Kruidhof and Pandy 2006; Vasavada et al. 2008; Ghezelbash, Arjmand, and Shirazi-Adl 2015). In addition, certain muscles such as the external and internal obliques are anatomically curved around the torso, so curved muscle geometry would serve as a more appropriate representation of realistic muscle geometry (Gatton, Pearcy, and Pettet 2001).

Realistic representations of curved muscle paths would be expected to significantly improve the accuracy of muscle-generated force and moment predictions relative to the joints. In addition, representations of curved muscle geometry could result in more realistic changes of muscle length that are important for defining muscle force-length and force-velocity relationships occurring during changes in postures or motions and, therefore, would provide more

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reliable muscle force and spinal load predictions (Arjmand, Shirazi-Adl, and Bazrgari 2006; Kruidhof and Pandy 2006). Kruidhof and Pandy (2006) found that curved muscle models of the cervical spine significantly altered muscle forces and joint moments compared to straight-line muscle models due to changed muscle moment arms. Arjmand, Shirazi-Adl, and Bazrgari (2006) also reported that muscle forces and spinal loads were substantially different over all lumbar disc levels due to the curved path of the lumbar spine extensor muscles.

However, only a few studies have systematically examined different techniques for representing curved muscle geometry and the underlying logic behind incorporating curved muscle models for the spine (Kruidhof and Pandy 2006; Vasavada et al. 2008). Kruidhof and Pandy (2006) and Vasavada et al. (2008) illustrated underlying assumptions and limitations of several muscle path techniques including the straight and curved muscle paths. However, none of studies has conducted a systematic literature review to obtain a comprehensive understanding of curved muscle models for the spine, such as the curved muscle techniques, muscle geometry, muscle function, muscle mechanics, model validation capability, and applied tasks.

The objective of the current literature review was to categorize different curved muscle techniques and evaluate their underlying assumptions for application to spine modeling. This review is intended to assist in more accurate model development and illuminate future needs for curved muscle spine models.

2. Methods

A systematic literature review was conducted via PubMed, Web of Science, Science Direct and Scopus. In addition, Google Scholar was used to search international conference proceedings. In order to be selected in this literature review, the following 16 keywords were used to gather relevant studies: (1) 'muscle', and (2) 'spine' or 'neck' or 'back' or 'trunk' or 'cervical' or 'thoracic' or 'lumbar', and (3) 'model', and (4) 'curved' or 'curved path' or 'wrapping' or 'wrapped' or 'via point' or 'obstacle set' or 'wrapping surface'. Additional criteria included language in 'English' and a study population of 'humans'. Articles cited in all retrieved studies were also searched to gather additional sources.

The resulting studies were screened based on their title, abstract or full text to meet several criteria for this study. First, the study must have developed or applied curved muscle geometry in the cervical, thoracic or lumbar spine. Secondly, the study must have implemented curved muscle geometry into a biomechanical model of the spine. Studies that did not clearly mention curved muscle techniques (even though it could have been included in earlier studies) were excluded.

Selected studies were incorporated into one of three categories based on curved muscle technique: (1) 'via-point' method, (2) 'obstacle-set', and (3) 'other' method. They were also categorized by seven different biomechanical modeling characteristics: (1) spine location, (2) static/dynamic, (3) task, (4) muscle geometry, (5) muscle function, (6) muscle mechanics, and (7) validation. When studies lacked clarification on any of these characteristics, a general description was applied. With respect to validation, an additional quantitative analysis was conducted to summarize the overall performance of curved muscle models as a function of different approaches taken by the reviewed studies.

There were two general approaches to assess curved muscle geometry and implement this information into a biomechanical model. First, the 'via-point' method was the primary approach to incorporate muscle wrapping in lower extremity biomechanical models (Delp et al. 1990; Delp and Loan 1995). In this method, straight-line or curved muscles were constrained by intermediate 'via-points' along the muscle path to generate realistic curved muscle paths as the joint moved. Second, the 'obstacle-set' or wrapping surface method, used for both upper and lower extremity biomechanics models (van der Helm and Veenbaas 1991; Arnold et al. 2000; Garner and Pandy 2000), employs straight-line or curved muscles that wrap around pre-defined shapes or rigid bodies (such as cylinders or spheres) to generate curved muscle paths around the joint. The interactive portion between muscles and obstacles was referred to as an 'obstacle-set' (Garner and Pandy 2000). Both of these curved muscle techniques have been implemented in spine biomechanics models.

For biomechanical modeling characteristic classifications, (1) 'spine location' referred to portion of the spine considered and was either cervical, thoracic or lumbar spine; (2) the 'static/dynamic' term referred to the capability of the biomechanical model to assess just static postures or also dynamic motions; (3) the 'task' term referred to the types of exertions evaluated by the biomechanical models; (4) the 'muscle geometry' term referred to the types of muscle data used to create curved muscle geometry; (5) the 'muscle function' term referred to the technique(s) used to estimate muscle forces (i.e. based on kinematics, kinetics, anthropometry, MRI, CT or electromyography (EMG) of muscles); (6) the 'muscle mechanics' term referred to the types of the mechanical/mathematical simulation of muscle forces to represent curved or wrapping characteristics of muscles; and (7) the 'validation' term considered how the model verified model fidelity, sensitivity or other advantages of implementing curved muscle geometry.

Table 1. Studies that used the 'via-point' method for biomechanical modeling.

Study #	Author	Spine Location	Static/Dynamic	Task	Muscle Geometry	Muscle Function	Muscle Mechanics
1	van der Horst et al. (1997)	Cervical	Dynamic	Impact	Literature data	Inverse dynamics	Tensile forces
2	Vasavada, Li, and Delp (1998)	Cervical	Dynamic	Single-plane motion	Literature data	Inverse dynamics	Tensile forces
3	Brolin, Halldin, and Leijonhufvud (2005)	Cervical	Dynamic	Impact	Literature data	Inverse dynamics	Tensile forces
4	Kruidhof and Pandy (2006)	Cervical	Static	Single-plane posture	Literature data	Inverse dynamics	Tensile forces
5	van Lopik and Acar (2007)	Cervical	Dynamic	Single-plane motion	Literature data	Inverse dynamics	Tensile forces
6	Vasavada, Brault, and Siegmund (2007)	Cervical	Dynamic	Automobile impact	Literature data	Inverse dynamics	Tensile forces
7	Vasavada et al. (2008)	Cervical	Static	Single-plane posture	MRI	Inverse dynamics	Tensile forces
8	Jaeger, Mauch, and Markert (2012)	Cervical	Static	Single-plane posture	MRI	Inverse dynamics	Tensile forces
9	Suderman and Vasa-vada (2012)	Cervical	Static	Single-plane posture	MRI	Inverse dynamics	Tensile forces
10	Cox et al. (2014)	Cervical	Dynamic	Single-plane motion	Literature data	Inverse dynamics	Tensile/Contact forces
11	Dong et al. (2015)	Cervical	Dynamic	Impact	Literature data	Optimization/in-verse dynamics	Tensile/Contact forces
12	Takashima et al. (1979)	Thoracic, Lumbar	Static	Upright posture	Literature data	Inverse dynamics	Tensile forces
13	Hatakeyama et al. (2011)	Thoracic, Lumbar	Dynamic	Standing	MRI	Inverse dynamics	Tensile forces
14	Yoshikawa et al. (2013)	Thoracic, Lumbar	Dynamic	Single-plane motion	MRI	Inverse dynamics	Tensile forces
15	Santaguida and McGill (1995)	Lumbar	Static	Single-plane posture	MRI	Statics	Tensile forces
16	Nussbaum and Chaffin (1996)	Lumbar	Static	Single-plane posture	Literature data	Statics	Tensile forces
17	Cholewicki and McGill (1996)	Lumbar	Dynamic	Sweeping, pull-ing, pushing, lifting	Literature data	Distributed EMG/ optimization	Tensile forces
18	van Dieën and Kingma (2005)	Lumbar	Dynamic	Seated tasks, pulling, push-ing, lifting	Literature data	Distributed EMG/ optimization	Tensile forces
19	Arjmand, Shirazi-Adl, and Bazrgari (2006)	Lumbar	Quasistatic	Static lifting	Literature data	Optimization/in-verse dynamics	Tensile/Contact forces
20	Bazrgari, Shirazi-Adl, and Arjmand (2007)	Lumbar	Dynamic	Squat and stoop lifting	Literature data	Optimization/in-verse dynamics	Tensile/Contact forces
21	Bazrgari and Shira-zi-Adl (2007)	Lumbar	Dynamic	Squat and stoop lifting	Literature data	Optimization/in-verse dynamics	Tensile/Contact forces
22	de Zee et al. (2007)	Lumbar	Quasistatic	Upright position	Literature data	Optimization/in-verse dynamics	Tensile forces
23	Arjmand et al. (2008)	Lumbar	Quasistatic	Static lifting	Literature data	Optimization/in-verse dynamics	Tensile/Contact forces
24	Bazrgari, Shirazi-Adl, and Larivière (2009)	Lumbar	Quasistatic	Sudden loading	Literature data	Optimization/in-verse dynamics	Tensile/Contact forces
25	Rasmussen, Tørholm, and de Zee (2009)	Lumbar	Static	Seating	Literature data	Optimization/in-verse dynamics	Tensile forces
26	Arjmand et al. (2010)	Lumbar	Quasistatic	Asymmetric lifting	Literature data	Distributed EMG/ optimization/ inverse dy-namics	Tensile/Contact forces
27	Christophy et al. (2012)	Lumbar	Dynamic	Single-plane motion	Literature data	Optimization/in-verse dynamics	Tensile forces
28	Han et al. (2012)	Lumbar	Dynamic	Single-plane posture	Literature data	Optimization/in-verse dynamics	Tensile forces
29	Han et al. (2013)	Lumbar	Dynamic	Single-plane posture, lift-ing, carrying	Literature data	Optimization/in-verse dynamics	Tensile forces
30	Hajihosseinali et al. (2014)	Lumbar	Quasistatic	Holding	Literature data	Optimization/in-verse dynamics	Tensile/Contact forces
31	Ghezelbash, Arjmand, and Shirazi-Adl (2015)	Lumbar	Static	Lifting	Literature data	Optimization/in-verse dynamics	Tensile/Contact forces

Table 2. Studies that used the 'obstacle-set' method for biomechanical modeling.

Study #	Author	Spine Location	Static/Dynamic	Task	Muscle Geometry	Muscle Function	Muscle Mechanics
6	Vasavada, Brault, and Siegmund (2007)	Cervical	Dynamic	Automobile impact	Literature data	Inverse dynamics	Tensile forces
7	Vasavada et al. (2008)	Cervical	Static	Single-plane posture	MRI	Inverse dynamics	Tensile forces
32	Suderman, Krishnamoorthy, and Vasavada (2012)	Cervical	Static	Single-plane posture	MRI	Inverse dynamics	Tensile forces
33	Gatton, Pearcy, and Pettet (2001)	Lumbar	Static	Single-plane posture	Literature data	Inverse dynamics	Tensile forces
22	de Zee et al. (2007)	Lumbar	Quasistatic	Upright position	Literature data	Optimization/inverse dynamics	Tensile forces
25	Rasmussen, Tørholm, and de Zee (2009)	Lumbar	Static	Seating	Literature data	Optimization/inverse dynamics	Tensile forces
34	Stokes, Gardner-Morse, and Henry (2010)	Lumbar	Quasistatic	Upright position	Literature data	Optimization/inverse dynamics	Tensile/Contact forces
35	Stokes, Gardner-Morse, and Henry (2011)	Lumbar	Quasistatic	Upright position	Literature data	Optimization/inverse dynamics	Tensile/Contact forces
13	Hatakeyama et al. (2011)	Thoracic, Lumbar	Dynamic	Standing	MRI	Inverse dynamics	Tensile forces
27	Christophy et al. (2012)	Lumbar	Dynamic	Single-plane motion	Literature data	Optimization/inverse dynamics	Tensile forces
14	Yoshikawa et al. (2013)	Thoracic, Lumbar	Dynamic	Single-plane motion	MRI	Inverse dynamics	Tensile forces
30	Hajihosseinali et al. (2014)	Lumbar	Quasistatic	Holding	Literature data	Optimization/inverse dynamics	Tensile/Contact forces

3. Results

The initial search using search items led to 67 hits in Web of Science, 79 hits in Scopus, and 49 hits in PubMed. Screening and judgement of the title, abstract and full text was initially conducted to exclude unrelated studies and duplications based on our strict criteria, then additional studies were found based on cited articles in retrieved studies. A total of 35 studies were finally selected, and eight of these included both the 'via-point' and 'obstacle-set' curved muscle modeling techniques. No other muscle wrapping techniques were discovered besides 'via-point' and 'obstacle-set'. Tables 1 and 2 describe the curved muscle modeling techniques employed for studies that used the 'via-point' and 'obstacle-set' techniques, respectively.

3.1. Curved muscle path

The 'via-point' method (31 studies) was used three times more often than the 'obstacle-set' method (12 studies) to define curved muscle path relative to the spine. This proportion was similar for each specific spine location with 11 studies vs. 3 studies for the cervical spine and 20 studies vs. 9 studies for the thoracic/lumbar spine.

3.1.1. Via-point method

Eleven of the thirty one studies that used the 'via-point' method developed curved muscle paths for the cervical spine, and 20 developed curved muscle paths for the thoracic or lumbar spine. The 'via-point' method was applied to various muscles surrounding the spine. For cervical spine models, muscle counts ranging from 1 to 30 were reported. For thoracic or lumbar spine models, the erector spinae muscle bundle was commonly modelled as a curved muscle due to its anatomically long muscle length.

3.1.2. Obstacle-set method

Twelve studies were categorized as using the 'obstacle-set' curved muscle modeling method. Three of these studies developed curved muscles for the cervical spine, and the other nine developed curved muscles for the thoracic/lumbar spine. For the surface geometric shape of cervical spine models, cylinders and spheres were commonly used to generate curved muscle paths for the sternocleidomastoid and semispinalis capitis muscles. Within the lumbar spine models, elliptical cylinders were commonly used to create curved muscle paths for external and internal oblique muscles.

3.2. Curved muscle model characteristics

3.2.1. Spine location

The curved muscle concept was more often employed in the thoracic/lumbar spine (23 studies) than the cervical spine (12 studies). The curved muscle concept for the thoracic/lumbar spine was investigated around 20 years earlier (1979 to 2015) than studies for the cervical spine (1997 to 2015).

3.2.2. Static/Dynamic

Static or quasi-static biomechanical modeling techniques (19 studies) were more commonly used than dynamic modeling techniques (16 studies). In addition, 88% of dynamic models (14 studies) were only tested in a single physiologic plane.

3.2.3. Task

Most studies (20 studies) evaluated basic theoretical exertions, such as upright posture, standing, single-plane posture or single-plane motions with their biomechanical models. A small number of studies (9) considered occupational lifting tasks such as static lifting, symmetric lifting, asymmetric lifting or squat and stoop lifting. A few studies (8) evaluated automobile impact testing, seated tasks, pushing, pulling, carrying, holding, or sweeping tasks.

3.2.4. Muscle geometry

Generic curved muscle geometry using previous literature data (28 studies) was more commonly used than person-specific muscle geometry (7 studies) based on MRI or CT data. The literature data generally consisted of published anatomic descriptions, MRI/CT database, and cadaveric dissections. When MRI or CT was used, only a single or a few subjects' muscle geometry was developed in the biomechanical model due to the limited sample size of medical imaging data resources in their studies.

3.2.5. Muscle function

Hybrid optimization/inverse dynamics models (15 studies) and inverse dynamics models (15 studies) were the most common approaches to estimate muscle forces or spinal loads regardless of spine location. Only a few EMG-driven models were discovered (3 studies). Hybrid inverse dynamics/optimization models typically optimized muscle recruitments, and they had to assume that agonists and antagonists behaved in certain optimal way.

3.2.6. Muscle mechanics

The tensile muscle forces (23 studies) were the most common approach to simulate the muscle forces of curved muscles. In addition to the tensile forces, 12 studies considered the sliding contact forces between muscles and bones to understand the effect of the muscle wrapping.

3.2.7. Validation

Table 3 shows the list of studies that clearly reported validation measures and performance of curved muscle models. In this table, the static/dynamic term referred to the capability of the model to validate just static postures or also dynamic motions. Regarding the curved muscle path, the 'via-point' method showed significantly lower prediction error rate (%) of compression than 'obstacle-set' method. Dynamic lumbar spine biomechanical models showed lower prediction error of compression than static biomechanical models. Pure inverse dynamics muscle function model showed lower prediction error of compression than hybrid muscle function models. Disc compression was generally calculated by the summation of multiple muscle forces vectors, and they were compared to intradiscal pressure of *in vivo* studies or predicted compression from other modeling studies. Generic muscle geometry models showed prediction error of moment from 43 to 263%, whereas a person-specific muscle geometry model had prediction error of compression as 0.4%.

For single-plane exertions, sagittal flexion tasks showed higher moment prediction error than sagittal extension, axial rotation, and lateral bending tasks for cervical spine models. Upright standing with no load showed higher intradiscal pressure prediction errors than with loaded conditions for thoracic/lumbar spine models (35% vs. 10%). For occupational tasks, complex tasks such as asymmetric lifting or pulling tended to have higher peak muscle force prediction errors than simple tasks for thoracic/lumbar spine models. The peak muscle force was measured by the summation of the peak force magnitude of all muscles in the model. The symmetric lifting tasks showed lower peak muscle force prediction errors than asymmetric lifting tasks (2% vs. 4%). Pulling (22%) and seated tasks (16%) showed higher peak muscle force prediction errors than lifting tasks (3%).

4. Discussion

This literature review examined the use of curved muscles in biomechanical models of the spine. Based on this systematic evaluation, the most common curved muscle models used the 'via-point' method, modelled the thoracic/lumbar spine location, employed a static/quasi-static approach, and looked at single-plane tasks. In addition, they used generic muscle geometry, used hybrid optimization/inverse dynamics muscle function, simulated tensile muscle force mechanics, and validated by comparing to results reported in previous literature. It is important to note that the most common approach does not necessarily constitute the best approach for curved muscle representations. A deeper dive into each validation measure and each component of different curved muscle

Table 3. Quantitative summary of validation measures and performances as a function of approaches in curved muscle models.

Task	Study #	Curved muscle path: Via-point	Curved muscle path: Obstacle-set	Static/Dynamic: Static	Static/Dynamic: Dynamic	Muscle geometry: Generic	Muscle geometry: Person-specific	Muscle function: Inverse dynamics	Muscle function: Hybrid	Validation: Measures	Validation: Prediction error (%)
Flexion	2	√		√		√		√		Moment	10.5 Nm (263%)
	5	√		√		√		√		Moment	Within range (15–30Nm)
	8	√		√			√	√		Muscle length	65%
	9	√		√			√	√		Muscle path	3.88 mm (*)
	32		√	√			√	√		Muscle path	3.39 mm (*)
	10	√		√		√		√		Muscle path	9.5 mm (*)
Extension	2	√		√		√		√		Moment	Within range (24–36 Nm)
	9	√		√			√	√		Muscle path	3.67 mm (*)
	10	√		√		√		√		Muscle path	10.4 mm (*)
Axial rotation	2	√		√		√		√		Moment	Within range (9–11 Nm)
	5	√		√		√		√		Moment	Within range (6–15 Nm)
Lateral bending	2	√		√		√		√		Moment	10 Nm (43%)
	5	√		√		√		√		Moment	Within range (16–36 Nm)
	32		√	√			√	√		Muscle path	8.16 mm (*)
Upright Standing With no load	34, 35		√	√		√			√	Compression	250 N (100%)
	13	√		√			√	√		Compression	3 N (0.4%)
	28	√		√		√			√	Compression IDP	45 N (10%) 0.13Mpa (35%)
Upright standing with load	30		√	√		√			√	IDP	0.24 Mpa (10%)
Sudden loading	24	√		√		√			√	Muscle force variation	0.3 (30%)
Frontal crash impact	11	√			√	√			√	Head rotation velocity variation	0.13 (13%)
Symmetric lifting	34, 35		√	√		√			√	Compression	798 N (66%)
	18	√			√	√			√	PMP	109 N (2%)
	21	√			√	√			√	Muscle stiffness coefficient	Within range (0.5–170)
	31	√		√		√			√	IVT	Within range (<2 mm)
Asymmetric lifting	18	√			√	√			√	PMP	184.25 N (4%)
Pulling	18	√			√	√			√	PMP	707 N (22%)
Sweeping	17	√			√	√			√	Compression	Within range (1500–3400 N)
Seated tasks	18	√			√	√			√	PMP	225.33 N (16%)

Notes: IDP = Intradiscal pressure; IVT = Intervertebral translations; PMP = Total peak muscle force.
*No predicted and actual values were reported, therefore percentage could not be calculated.

modeling techniques is discussed here to illuminate future recommendations.

Cervical spine and thoracic/lumbar spine models used different types of validation measures. Cervical spine models mainly considered the moment-generating capacity and muscle path deviation, whereas lumbar spine models mainly considered compression spinal loads, total peak muscle force, and moment matching. Even though several models were originally categorized as dynamic models based on the capability (Tables 1 and 2), only a few studies actually validated their models during dynamic conditions (Table 3). Most cervical spine models only validated their models during static exertions based on pure inverse dynamic muscle function. This indicates that a disparity existed between the dynamic 'capability' of models and the dynamic 'validity' of those models.

Static moment-generating capacity was often used to validate cervical spine models. The moment-generating capacity was calculated as the product of muscle moment-arms and maximum isometric force. These predicted values were generally compared with the measured values from different subject group of previous experimental study of human neck strength in certain positions such as upright or sagittal bending positions. However, when calculating the total moment-generating capacity, all muscles surrounding the spine were assumed as maximally activated simultaneously. This assumption might not accurately represent realistic coactivation patterns and, therefore, may not be valid since different activation of agonist and antagonist muscles would alter the net moment produced. In addition, static moment-generating capacity was mainly tested during upright or sagittal-only postures. Moment-generating capacity of complex asymmetric postures or dynamic motions was not investigated.

Muscle path deviation was also used by some studies to validate the curved muscle geometry of the cervical spine. Curved muscle paths based on 'via-point' method or 'obstacle-set' method in models of the cervical spine was compared with the MRI-derived muscle centroid paths by calculating the average deviation between the two paths. This measure was able to validate the curved muscle paths in certain static positions such as upright or single-plane postures. However, this method has not investigated in coupled-plane postures, and only a few muscles were analyzed.

Disc compression was often used to validate thoracic/lumbar spine models. These predicted compression values were typically compared to the range of the measured intradiscal pressure of *in vivo* studies or predicted compression values from other modeling studies. This comparison validation was limited to only certain exertions that were reported in previous literature. Even though this comparison could evaluate if predicted compression values were within the range of previous values, validation of specific tasks or a specific individual was not possible with this approach.

Total peak muscle force was also considered as a means to validate thoracic/lumbar spine models. This measure summed the peak resultant force magnitude of all muscles. For example, the total peak muscle force between an EMG-based model and an optimization-based model was compared to validate the muscle force estimation of the optimization-based model (van Dieën and Kingma 2005). Even though this measure could be useful for the relative comparison between models, it does not lend any information about the accuracy or validity of either of the models.

Some thoracic/lumbar spine model studies used moment matching performance for validation. The coefficient of determination (R^2) was calculated to validate the dynamic moment pattern between estimated and measured moments at certain disc levels of the spine. Average or median absolute error (Nm) between estimated and measured moments was also calculated. For example, van Dieën and Kingma (2005) tested the moment matching performance of their EMG-based model during a range of static and dynamic occupational activities, and were able to evaluate the fidelity of their biologically-assisted model for each trial of individuals. Even though this study was only able to validate a single disc level (L5/S1) of the lumbar spine, This measure allowed the researchers to measure the validity of the model during complex dynamic exertions.

In summary, the moment matching measure seems to be the most promising validation measure because of its application to wide ranges of specific trials, individual subjects, and dynamic exertions. Most other measures were limited for use in single-plane static exertions, for comparing to historic ranges reported in the literature, or for cross-model comparison. Future studies should incorporate measurements of moment about intervertebral discs in order to effectively validate the characteristics of curved muscles during a variety of complex occupational tasks of individuals.

Based on this review, the 'via-point' method was the most common technique for developing curved muscle paths. In this method, 'via-points' were normally located between the origin and insertion of the straight-line or centroid path of curved muscles, and let each muscle divided into several segments. Those 'via-points' were attached to vertebral bodies or certain body segments of the spine. These constrained 'via-points' let the muscles lines of action follow the movement of the spinal column during changes in posture. Since 'via-points' were rigidly linked to the bones or body parts, muscle forces were transmitted to vertebral bodies or body segments through the 'via-points' in the model (de Zee et al. 2007).

However, 'via-points' along muscles were normally set in an upright posture, and the distance between 'via-points' and bones were fixed during changes of postures or motions. Thus, these studies did not consider the deformation of soft tissue during non-neutral postures or motions. Suderman and Vasavada (2012) suggested moving muscle points to overcome this deformation issue in their cervical spine model. In this method, moving muscle points were created from the smoothed centroid muscle paths of five different sagittal plane neck postures using MRI. This approach showed more accurate muscle moment arms than 'via-points' or straight-line methods, but it required multiple postures using MRI, and it was only verified for single sagittal plane postures in two subjects.

The 'obstacle-set' method was another common technique to develop curved muscle paths for the spine. In this method, curved muscle paths were affected by the shape, orientation, size and location of wrapping geometric surfaces (Vasavada et al. 2008). This approach was less frequently used for spine models compared to other upper or lower extremity models (van der Helm and Veenbaas 1991; Garner and Pandy 2000). Since the spinal column consists of a series of multiple vertebral bodies and a complex system of ligaments, development of an effective wrapping surface has been more challenging than for other types of anatomical structures such as the joint capsule of the knee or elbow. Vasavada et al. (2008) investigated the objective process to select proper shape, orientation, size and location of wrapping geometric surfaces of several cervical spinal muscles. This study showed promising results with accurate muscle moment arms, but it was only applicable to a few muscles, and only tested during single-plane exertions.

With regards to modeling performance, the 'via-point' method showed significantly lower prediction error of compression than the 'obstacle-set' method of the lumbar spine model. The 'via-point' method was applied to the centroid path of trunk muscles based on the literature data including CT, MRI, and cadaver data (Cholewicki and McGill 1996), whereas the 'obstacle-set' method was applied to the layers of abdominal muscles (Stokes, Gardner-Morse, and Henry 2011). The difference of performance might be partially due to the simplified generic elliptical shape of abdominal wall using the 'obstacle-set' method (Stokes, Gardner-Morse, and Henry 2010) compared to detailed muscle geometry used for the 'via-point' method (Cholewicki and McGill 1996). However, compression validation measure by literature comparison was not possible to validate specific tasks or specific individuals.

In addition, there were eight studies that employed both 'via-point' and 'obstacle-set' method (Tables 1 and 2). Among them, only one study performed a direct comparison of the modeling performance between two curved muscle techniques (Vasavada et al. 2008). Vasavada et al. (2008) reported that the 'obstacle-set' method showed an average 12% additional error of the muscle path compared to 'via-point' technique (muscle centroid path) for the sterno-mastoid and semispinalis capitis muscles during various static postures including the neutral, flexion, extension, axial rotation, lateral bending, protraction, and retraction. This result was similar to the previous trend of indirect comparison in compression measures.

Many curved muscle models were used to evaluate static or quasi-static conditions. These static or quasi-static models were able to represent static exertions, but were not applicable to dynamic exertions because they did not account for different physiological responses such as muscle force-velocity relationships (Granata and Marras 1995; Marras and Granata 1997). Several dynamic models were developed with curved muscles. However, only simple, single-plane motions were typically investigated, while complex or coupled dynamic motions or realistic occupational tasks and activities of daily living were rarely considered.

With regard to the model performance, even though several models were categorized as dynamic models (Tables 1 and 2), only 4 studies (Cholewicki and McGill 1996; van Dieën and Kingma 2005; Bazrgari and Shirazi-Adl 2007; Dong et al. 2015) validated the model fidelity during dynamic exertions (Table 3). Compression measure was a common validation measure between static models (Hatakeyama et al. 2011; Stokes, Gardner-Morse, and Henry 2011; Han et al. 2012) and a dynamic model (Cholewicki and McGill 1996). As mentioned earlier, compression values were usually compared with the trend of values from previous studies, so precise comparison of the performance between static and dynamic models was not possible. In addition, since only one study performed compression validations during dynamic exertions, conclusive result from comparison might be difficult in this review.

As a moment matching measure, van Dieën and Kingma (2005) considered moment matching performance at L5/S1 to validate an EMG-based model during a range of static and dynamic occupational tasks. This study showed the median R^2 as 0.87 and median absolute moment error as 10.9Nm across all trials. This approach showed good model fidelity, and was able to validate each specific trial for individuals. Based on these validation reports, dynamic curved muscle models of the lumbar spine were considered as a reasonable approach.

Single-plane postures or single-plane motions were frequently evaluated with curved muscle models. In particular, eight studies evaluated these types of tasks with cervical muscle models, whereas no occupational tasks were evaluated. Lifting was the most common occupational tasks studied in thoracic/lumbar spine models. However, most lifting tasks were sagittal plane symmetric lifting, and only a few studies considered asymmetric, squat, or stoop lifting.

Many curved muscle models have developed generic curved muscle geometry based on previous literature data. In order to develop personalized curved muscle geometry, several studies have used the MRI or CT of individual subjects (Vasavada, Li, and Delp 1998; Kruidhof and Pandy 2006; Hatakeyama et al. 2011; Jaeger, Mauch, and Markert 2012; Suderman and Vasavada 2012). However, only a few personalized curved muscle models have been developed due to the limited sample size for available medical imaging data. For the cervical spine model, Vasavada et al. (2008) developed the personalized muscle centroid path based on MRI of one male subject. For the thoracic/lumbar spine model, Hatakeyama et al. (2011) developed the personalized muscle geometry using the MRI and CT data of one male subject.

Person-specific muscle models generally showed lower prediction error of moment-generating capacity (Nm) than generic muscle models. Person-specific muscle geometry included the individual variation of muscle centroid path and it could be more accurate and sensitive to the changes of muscle moment-arms. Vasavada, Li, and Delp (1998) found that changes of moment-arms significantly affected the magnitude of moment-generating capacity. However, only one person-specific muscle model was included for the comparison of moment-generating capacity, so it was difficult to generalize the result.

The inverse dynamics method was one of the most common methods used to estimate muscle forces across the studies. This method calculates the reaction forces and moments at certain joint centers based on known or measured forces at the feet or hands using force transducers (Kingma et al. 1996). Given these values, muscle forces are inversely calculated to resolve the redundancy of moment equilibrium equations about a certain joint.

The application of inverse dynamics models to complex exertions found in this review was limited. For example, pure inverse dynamics models have tested only upright standing postures and single-plane exertions, whereas hybrid muscle models often tested complex occupational tasks. For example, Cholewicki and McGill (1996) reported that compression estimation of a biologically-assisted model during sweeping task was within the ranges of values from other modeling studies.

Though the inverse-dynamics method produces good moment matching, it does not distribute realistic complex co-activations of muscles during various exertions (Kingma et al. 1998) and, therefore, is unlikely to accurately predict force. Studies have shown that ignoring co-activations could result in underestimation of compression spinal loads by 45% and shear loads by up to 70% (Granata and Marras 1999). To overcome this issue, biologically-assisted models directly measure muscle activities of the major power-producing muscles of the spine for each individual subject (Marras and Sommerich 1991). In order to consider the force estimation of deep muscles that cannot be reliably reached by EMG, hybrid methods using distributed EMG, optimization, or inverse dynamics methods have also been suggested (van Dieën and Kingma 2005), however the application of these methods have not been actively validated for curved muscle models of the spine.

In terms of the muscle mechanics, most models only considered the tensile muscle forces to simulate the effect of curved muscles on the spinal loads. For example, tensile muscle forces between origins and insertions of curved muscles were generally transmitted through the 'via-points' to the vertebral bodies or other body parts. However, Arjmand, Shirazi-Adl, and Bazrgari (2006) reported that contact forces between muscles and vertebral bodies should be additionally accounted to simulate the proper mechanical effect of wrapping muscles. They found that contact forces primarily increased anterior shear loads at lower lumbar levels (L3 to S1), and slightly improved the spinal stability. In order to properly account for the mechanical and geometrical aspect of curved muscles, hybrid 'via-point'/'wrapping(-contact)' approach might enhance the accuracy of the models in the future.

This review has helped identify several potential research directions for future muscle curvature studies. First, concerning curved muscle paths, the deformation of soft tissue during changes of postures or motions should be investigated to better understand the realistic physiological characteristics of muscles during movement.

Second, complex dynamic exertions were rarely studied by curved muscle models. Yet, in occupational settings and activities of daily living, complex asymmetric exertions that combine motion in three dimensional space are common, and it is known that these types of exposures significantly increase risk of spine disorders (Marras et al. 1993). Thus, more robust curved muscle models are needed to better document the tissue loading associated with these complex dynamic loading conditions.

Third, existing models commonly have used literature data including published anatomic descriptions, MRI/CT database, and cadaveric dissections of muscle geometry to develop curved muscles. In addition, several models have developed person-specific muscle geometry using CT or MRI, but with limited sample size. Future studies might consider the development of predictive models of person-specific curved muscle geometry based on CT, MRI or anthropometric data. This approach would allow researchers to efficiently personalize muscles for individual subjects and could be applied to a large number of individuals.

Given that there are several different approaches used to represent curved muscles, a question still remains as to what method is the most appropriate. To answer this question, theoretical and empirical validations of curved muscle models that account for realistic muscle forces and coactivations through EMG would be required. Person-specific and task-specific validations of curved muscle models during static and dynamic exertions would help understand potential physiological and functional characteristics of personalized curved muscle models. In addition, application of curved muscle models to realistic occupational tasks such as dynamic lifting, lowering, pushing, pulling, or carrying would verify empirical model fidelity.

5. Conclusions

This literature review systematically summarized existing techniques for representing muscle curvature in biomechanical models of the spine. Most validations for these models were limited to static single-plane exertions, trend comparison with literature, or cross-comparison between models. The moment matching measure was found to be the most effective approach for evaluating the performance of dynamic models for specific tasks, and specific individuals.

Cervical spine models actively developed person-specific curved muscle geometry, but a few studies validated models during dynamic exertions or utilized biologically-assisted muscle function. Thoracic/lumbar spine models mainly used generic curved muscle geometry based on the literature including MRI/CT database and cadaveric dissections, and only a few models validated hybrid biologically-assisted and optimization muscle function during static or dynamic occupational tasks.

The 'via-point' method generally performed better than the 'obstacle-set' method due to the limitation of simplified wrapping geometric surface in the 'obstacle-set' method. Person-specific muscle geometry tended to have lower prediction error of moment than generic muscle geometry partially due to the accurate representation of individual variance of muscle moment-arms. In addition to tensile muscle forces, contact forces between muscles and bones were useful to understand the mechanical effect of muscle wrapping. The validation of inverse dynamics models was limited to static postures, whereas biologically-assisted models showed promising model fidelity during dynamic occupational tasks and are expected to predict more realistic muscle forces due to the proper account of muscle coactivation.

Future studies should explore the potential functional and anatomical characteristics of curved muscles, deformation of soft tissue, personalized muscle geometry and function including measured coactivation, and application to complex, dynamic activities of daily living and occupational tasks. This review serves to better elucidate the current level of understanding of the various techniques and underlying logic used to develop curved muscle models, and suggests future research directions for curved muscle model development in order to better understand how tasks contribute to spine tissue loading and potentially spine disorders.

Disclosure statement

No potential conflict of interest was reported by the authors.

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