INTRODUCTION: The lumbar spine needs to be stable and flexible for performing various daily activities without the collapse of the upper body. It was recently shown that, when the forces resulting from the body weight, muscle forces and external loads are directed along the spinal curvature (follower load), the ligamentous lumbar spine can become a stable column with small loss of range of motion. It was also shown that such a follower compressive load (FCL) may be established in sagittal plane by lumbar muscles. The purpose of this study was to investigate: 1) if the lumbar muscles can produce FCLs in the lumbar spine within the range of MFC; and 2) if so, what is the effect of MFC on FCL and muscle activation patterns.

METHODS: Assuming mid sagittal symmetry, a 2-D optimization problem was formulated to determine the muscle forces required to produce the follower load while maintaining a quiet standing neutral posture (lumbar lordosis angle of 27°). For this purpose, a total of 64 lumbar muscle components that should be effective in sagittal plane were modeled (Fig 1) using reported information of the origin and insertion points of each fascicle. The simulated muscles consisted of 22 long muscles (6 psoas major, 5 quadratus lumbarum, 1 rectus abdominis, and 2 spinalis intertransversarii, and 11 rotatores).

The objective (or cost) functions were the summation of joint (follower) forces and the summation of the joint moments. These were added with the weighting factors to transform the two objective functions into a single objective function. Both weighting factors were determined as 1.0 to evenly minimize the summation of joint forces and moments. The equality constraints were the force equilibrium equations in each vertebral joint, whereas no optimization solution could be found when the follower load path was assumed to be out of the range of 11 mm. Minimum FCLs were predicted when the follower load path was assumed by connecting the points 7 mm posterior to GCs. Their magnitudes were 430.4 N at T12-L1, L1-L2, L2-L3 and L3-4 joints, 447.7 N at L4-L5 joint, and 461.2 N at L5-S1 joint. Active muscle forces were predicted in spinalis thoracis L1-T6 (73 N), rotatores L1-T12 (70 N), interspinales L2-L1 (23 N), intertransversarii L2-L1 (34 N), rotatores L2-L1 (73 N), interspinales L3-L2 (5 N), intertransversarii L3-L2 (78 N), rotatores L3-L2 (32 N), longissimus sac-L3 (36 N), multifidus sac-L3 (6 N), interspinales L4-L3 (6 N), intertransversarii L4-L3 (56 N), longissimus sac-L4 (75 N), interspinales L5-L4 (4 N), and longissimus sac-L5 (11 N), while forces in the other muscles were all zero. FCL changes due to follower load path variation are shown in Fig 3 where the variation in the maximum FCL, which always occurred at L5-S1 level, is shown as a function of FLP changes. Within the FLP range of 11 mm, the joint reaction moments were predicted to be zero at all intervertebral levels. When the FLP was set anteriorly from the 7 mm curve, the additional contribution of psoas major was needed to establish FCL in most lumbar levels.

For MFC = 45 N, the solution is similar to the previous case except for the narrower FPR, 7 mm band from 2 mm to 9 mm posterior shift from the GC connecting curve. FCL changes due to follower load path variation are also shown for MFC = 30 N, the FPR becomes narrower to 5 mm (4 - 9 mm posterior shift) and the FCLs along 4 and 5 mm posteriorly shifted FLP showed significant increases from the previous two cases of larger MFCs as shown in Fig 3.

RESULTS: When MFC was 90 N/PCSA, the solution for muscle forces was converged within the follower load path (FLP) range from 9 mm posterior shift to 2 mm anterior shift from the pathway connecting the GCs of the vertebra, whereas no optimization solution could be found when the follower load path was assumed to be out of the range of 11 mm. Minimum FCLs were predicted when the follower load path was assumed by connecting the points 7 mm posterior to GCs. Their magnitudes were 430.4 N at T12-L1, L1-L2, L2-L3 and L3-4 joints, 447.7 N at L4-L5 joint, and 461.2 N at L5-S1 joint. Active muscle forces were predicted in spinalis thoracis L1-T6 (73 N), rotatores L1-T12 (70 N), interspinales L2-L1 (23 N), intertransversarii L2-L1 (34 N), rotatores L2-L1 (73 N), interspinales L3-L2 (5 N), intertransversarii L3-L2 (78 N), rotatores L3-L2 (32 N), longissimus sac-L3 (36 N), multifidus sac-L3 (6 N), interspinales L4-L3 (6 N), intertransversarii L4-L3 (56 N), longissimus sac-L4 (75 N), interspinales L5-L4 (4 N), and longissimus sac-L5 (11 N), while forces in the other muscles were all zero. FCL changes due to follower load path variation are shown in Fig 3 where the variation in the maximum FCL, which always occurred at L5-S1 level, is shown as a function of FLP changes. Within the FLP range of 11 mm, the joint reaction moments were predicted to be zero at all intervertebral levels. When the FLP was set anteriorly from the 7 mm curve, the additional contribution of psoas major was needed to establish FCL in most lumbar levels.

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