Risk Estimation for Intervertebral Disc Pressure through Musculoskeletal Joint Reaction Force Simulation

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Abstract— **This research proposes a novel method that evaluates joint reaction forces by motion analysis using a musculoskeletal model. While general muscle tension estimations minimize the sum of the muscle tensions, the proposed method utilizes the joint reaction forces themselves in the objective function of the optimization problem in addition to conventional method. This method can estimate a pattern of the muscle tensions that maximizes or minimizes a specific joint force. As a typical outcome, the proposed method allows evaluating intervertebral disc compressive force caused by co-contraction of muscles while avoiding risk underestimation. We analyzed the actual lifting motion as an example and confirmed that the method can estimate the muscle tension distribution under different tension conditions.**

I. INTRODUCTION

The back pain has been one of the serious physical health problems of workers for a long time. One of the causes of the low back pain is an overload on the intervertebral discs. The National Institute of Occupational Safety and Health (NIOSH) in the United States provided the information about criteria for compressive forces which the disc can tolerate [1]. The criteria are used worldwide for risk estimation of disc compressive force. It is highly probable that continuous work leading to excessive physical load over the reference value causes trouble of the lumbago. However, the intervertebral disc pressure is not possible to measure from the outside of the body, therefore, risk estimation by simulation model has been studied actively. Particularly in the occupational safety and health field, efforts have been made to evaluate work postures at actual work place using simplified human body models [1][2][3]. The warning systems of real-time load such as a wearable device [4] have been also developed. Most of these workload estimation methods deal with only two-dimensional movement (bending and extension of the waist), and simplify the degrees of freedom of a human skeleton model, and are specialized in load lifting motion. Such estimation methods with a simplified model have the following advantages: low calculation cost, intuitive understanding and easy to use. On the other hand, this simple estimation may result in underestimation of joint compression forces especially due to lack of accurate muscle co-contraction model. As a related research investigating realistic for such forces, Takahashi et al. measured the mechanical load of the lumbar spine by inserting a needle-type pressure sensor. They found that actual spinal loads during trunk flexion were larger than the theoretical values computed by only back muscle in its model, and concluded that the increase was caused by the muscle activity [5]. It is therefore necessary to develop a more precise method to overcome this disadvantage of simplified model.

In this study, we propose workload estimation by a musculoskeletal model including polyarticular antagonistic muscles. This model approximates a human body as rigid body links connected by joints, while muscles, tendons and ligaments are modeled as wires for generating joint torques. Recently, efficient computational algorithms have been developed for multibody systems such as human body and expand their scope of application, which enable analysis of the more complex model at higher speed [6]. Simulations using the musculoskeletal model calculate the joint torques or muscle forces which generate the input motion. Here, the wire tensions cannot be uniquely determined since the number of wires is redundant with respect to the number of degrees of freedom of the joint. Analytical methods are commonly used that average and minimize the burden on muscles, such as adopting the sum of squares of muscle tensions as an objective function. However, since muscle co-contraction are not taken into account, this analysis may cause underestimation of actual burden. Especially when the analysis is used for risk evaluation, to estimate possible risk is more important than to obtain the efficient muscle exertion.

We propose a novel wire tension estimation method of the musculoskeletal model with the optimization problem considering joint reaction forces. In addition to general muscle tension estimation, we introduce a new analysis by introducing a mapping matrix to convert the wire tensions to joint reaction forces. The major contribution is that the proposed method allows evaluating the potential risk coming from the workload by providing maximum joint reaction forces. As a representative application, the load estimation of the intervertebral disc compression force is presented.

II. METHOD

A. Estimation of muscle tensions

This section describes a general muscle tension estimation method without considering joint reaction forces. Our proposed method which is based on this method will be described in Section II-B.

In this research, a human musculoskeletal system is modeled as a set of rigid links obtained by dividing the skeleton with suitable precision, and the joints are approximated

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by rotational or spherical joint [6]. Muscles, tendons and ligaments are approximated as wires with attachment points on the skeleton and exert forces in the contraction direction. The equation of motion of the human link model is given by Eq.(1).

$$\boldsymbol{M}\ddot{\boldsymbol{q}} + \boldsymbol{b} = \boldsymbol{J}_J{}^T \boldsymbol{f} + \sum_{i=1}^{N_E} \boldsymbol{J}_{Ei}{}^T \boldsymbol{f}_{Ei} \tag{1}$$

where,

- $\boldsymbol{q}$ is the vector of the generalized coordinates,
- $\boldsymbol{M}$ is the inertia matrix,
- $\boldsymbol{b}$ is the Coriolis, centrifugal and gravity term,
- $\boldsymbol{f}$ is the vector of the wire tensions,
- $\boldsymbol{J}_J{}^T$ is the Jacobian matrix which convert the wire tensions to the generalized forces,
- $\boldsymbol{J}_{Ei}{}^T$ is the Jacobian matrix which convert the external force at contact point Ei to the generalized forces,
- $\boldsymbol{f}_{Ei}$ is the vector of external force exerted at contact point E_i.

Inverse dynamics is usually used to compute the wire tensions that satisfy this equation. For this analysis, we utilize dynamics computation library of musculoskeletal model by Nakamura et al [6]. First, joint torques $\boldsymbol{\tau}_J$ which realize the given motion ($\boldsymbol{q}$, $\dot{\boldsymbol{q}}$, $\ddot{\boldsymbol{q}}$, $\boldsymbol{f}_{Ei}$) are computed as follows:

$$\boldsymbol{\tau}_J = \boldsymbol{M}\ddot{\boldsymbol{q}} + \boldsymbol{b} - \sum_{i=1}^{N_E} \boldsymbol{J}_{Ei}{}^T \boldsymbol{f}_{Ei} \tag{2}$$

Then, the wire tensions $\boldsymbol{f} = [f_1\ f_2\ ...\ f_{N_w}]$ which realize the computed joint torques are calculated.

$$\boldsymbol{\tau}_J = \boldsymbol{J}_J{}^T \boldsymbol{f} \tag{3}$$

Since the wires exert tensions only in the contractive direction, each element is defined to be zero or less. Especially when f_j is the tension of muscle,

$$-\boldsymbol{f}_{max} \leq \boldsymbol{f} \leq \boldsymbol{0} \tag{4}$$

where, $\boldsymbol{f}_{max}$ is the maximum tensions of each muscle, which are calculated based on anatomical knowledge [7], [8]. Since the number of wires is redundant with respect to the number of generalized forces, $\boldsymbol{f}$ cannot be uniquely determined. Biomechanically reasonable index are therefore introduced for optimization calculations. In this paper, the quadratic programming problem is solved using an objective function such as defined in Eq.(5) under the inequality constraint condition Eq.(4) to obtain the wire tensions.

$$Z = \boldsymbol{f}^T \boldsymbol{W}_f \boldsymbol{f} + (\boldsymbol{\tau}_J - \boldsymbol{J}_J{}^T \boldsymbol{f})^T \boldsymbol{W}_\tau (\boldsymbol{\tau}_J - \boldsymbol{J}_J{}^T \boldsymbol{f}) \tag{5}$$

where, $\boldsymbol{W}_f$ and $\boldsymbol{W}_\tau$ are weighting matrices, which are diagonal matrices with positive values as diagonal elements. The first term is for minimizing the sum of squares of wire tensions, the second term is for minimizing the square sum of the error of the motion equation Eq. (3). The second term is ideally an equality constraint, however, the conditions are relaxed by incorporating them into the objective function in consideration of modeling errors of the human, motions and external forces.

B. Estimation in consideration of joint reaction forces

Here, a term performing joint force evaluation is added to the objective function Eq.(5), and analyzes the wire tensions as follows.

$$Z_c = Z + (\boldsymbol{\tau}_c - \boldsymbol{J}_c{}^T \boldsymbol{f})^T \boldsymbol{W}_c (\boldsymbol{\tau}_c - \boldsymbol{J}_c{}^T \boldsymbol{f}) \tag{6}$$

where,

- $\boldsymbol{W}_c$ is the weighting matrix with respect to joint reaction forces,
- $\boldsymbol{\tau}_c$ is the joint reaction forces obtained from the given motion and the external forces,
- $\boldsymbol{J}_c{}^T$ is the mapping matrix which convert the wire tensions to the joint reaction forces.

In II-A, only the generalized forces around the axis involved in the movement were taken into account. However, six axis forces $[\boldsymbol{F} \quad \boldsymbol{N}]$ consisting of translational forces $\boldsymbol{F}$ in three axial directions and moments $\boldsymbol{N}$ around each axis can be calculated for each joint actually from the given motion $(\boldsymbol{q}, \dot{\boldsymbol{q}}, \ddot{\boldsymbol{q}})$ and external forces $\boldsymbol{f}_{Ei}{}^T$. In the case where the axis receiving the force or the moment is a movable coordinate, the applied force generates motion, in contrast, in the case of the fixed coordinate, a balancing restraining force is generated so that it does not move. Comprehensive joint forces can be obtained by summing the calculated forces due to the motion $\boldsymbol{\tau}_c$ and the effect of wire tensions $-\boldsymbol{J}_c{}^T \boldsymbol{f}$. Among the joint reaction forces, in particular the one in the direction of the spinal column is generally called the intervertebral disc compressive force.

When the weight $\boldsymbol{W}_c$ of the objective function in Eq.(6) is positive, the corresponding joint force is decreased. It is increased conversely when the weight is negative value.

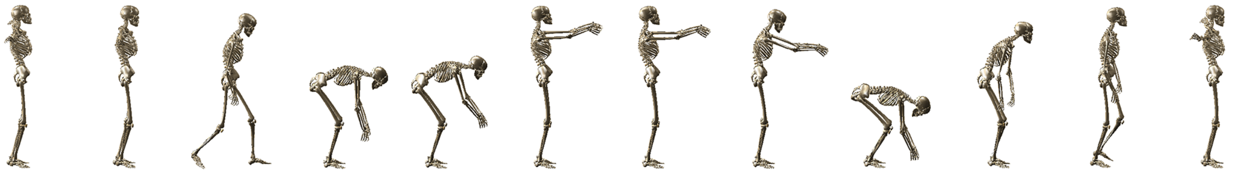


Fig. 1. Sequence of target motion.

In this case, the load estimation can be performed under the assumption that the muscles exert maximum burden on the joints, which can simulate the situation like the person stiffening the body with predicting the impact. In this paper, we refer to the analysis with the positive weights as “low risk” estimation, and the analysis with the negative value as “high risk” estimation. As this weight gets larger, other evaluation indexes are ignored and the error of generalized force increases. It is necessary to determine allowable error for each analysis and appropriately determine the weight matrix.

III. ANALYZED EXAMPLE

The proposed method mentioned in the previous section was applied to the analysis of the intervertebral disc compression force during lifting motion. Figure 1 illustrates the target motion that a human raises and lowers a package. The motion was measured by using an optical motion capture system. As a hand load, the human has 2.5 kg weights at his both hands, a total load is 5 kg. The human model is 54.4kg in weight, 1.68m in height, 47 DOF and has a total of 360 wires in the whole body. Especially the joints and muscles around the lumbar affect the intervertebral disc compression. Figure 2 shows the model around trunk and the wires that affect the lumbar vertebra. The link of trunk was divided at L5/S1 and T12/L1 into three segments (pelvis, Lumbar spine and Thoracic spine). The wires are nine longissimus thoracis muscles, six iliocostalis lumnorum muscles, four quadratus lumborum muacles, four rectus abdminis muscles, one abdominal external oblique muscle and one abdominal internal oblique muscle. These muscles were divided into several wires in consideration of the attachment points. The weights of the objective function of Eq. 6 were set experimentally so that the errors of the joint torques were within 10% for the simple motion that flexes the waist 45 degrees. The values are as follows:

- the diagonal elements w_τ of $\boldsymbol{W}_\tau$ are 1,
- the diagonal elements w_{f_j} of $\boldsymbol{W}_f$ are defined as follows:

$$w_{f_j} = \frac{w_f}{({f_j}^{max})^2} \tag{7}$$

  where, ${f_j}^{max}$ represents maximum tension of each muscle which is determined based on anatomical knowledge such as physiological cross-sectional area. Here, $w_f = 1$.

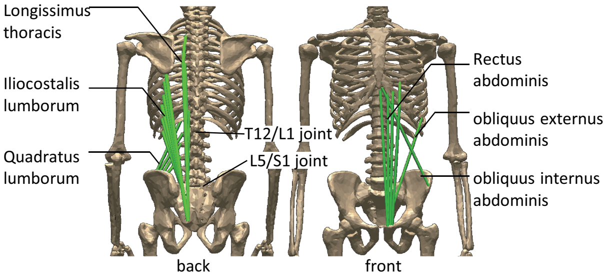


Fig. 2. Model of the trunk muscles of the left side and the joints.

- the diagonal elements w_c of $\boldsymbol{W}_c$ has value only in the disc compression direction and the others are zero. w_c is -3×10^{-5} for high risk estimation and 3×10^{-5} for low risk estimation.

For comparison, the normal muscle tension estimation with the objective function Eq.(5) without considering joint forces was also performed. The weight of each item is $w_\tau = 1$, $w_f = 20$.

Figure 3 shows the results of the calculation of the intervertebral disc compression forces. The graph at the bottom shows the transition of the compression forces between the fifth lumbar vertebra and sacrum. The red line, the blue line and the black line show the result of high risk, low risk and normal analysis respectively. The results shows that the load on the disc is higher under the high risk condition than the value from the normal estimation over the entire motion, and also the load is low under the low risk estimation. Figure 4 shows the results of computing the trunk muscle tensions at 9 seconds after the start of the motion. Here, if the spinal column is assumed to be modeled with one joint and driven by a pair of antagonistic muscles, either the active or antagonistic muscle should be the maximum tension when trying to maximize compressive force of the intervertebral disc. It means that the load is highest in an upright posture where the muscles are close to natural length and easy to exert forces, and the compression due to the muscle decreases when forward bending. However, by modeling with muscles straddling multiple joints as shown in Fig. 2, muscle tensions do not necessarily become the maximum value in all postures, because the muscle tensions need to maintain the equilibrium of force at multiple joints simultaneously. Therefore, this model provides estimates of more natural muscle exertion including the effect of co-contraction. Figure 4 shows that the muscle tensions are distributed to the back muscles when normal estimation, whereas in the low-risk condition, the output of the muscles with high forces in the disc compression direction are selectively decreased. Moreover, under the high-risk condition, the activities of the muscles along the compressive direction increase and the activities of the abdominal muscles are also increased.

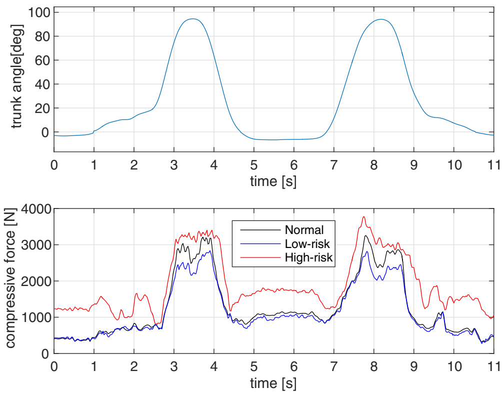
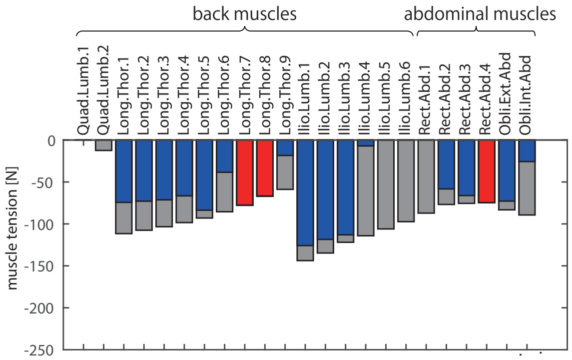
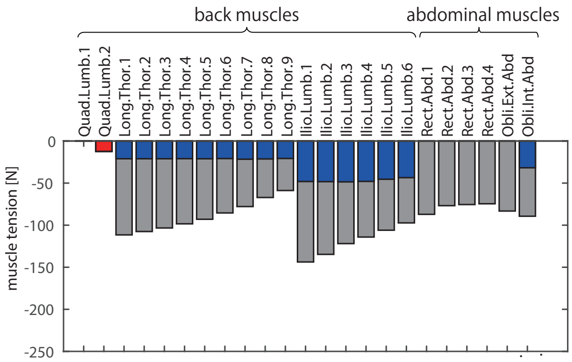


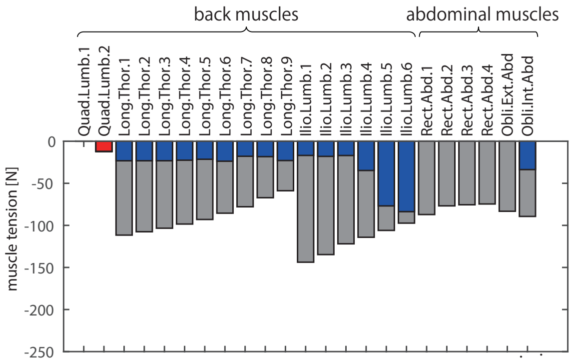
Fig. 3. Results of compression force at L5/S1 joint.



(a) high risk condition



(b) without compression criteria



(c) low risk condition

Fig. 4. Results of wire tension estimations at the frame 9 seconds after the motion start. The muscles were divided into several wires and numbered. Gray bar represents maximum tension in each muscle and posture. Blue bar represents computed tension and red bar shows that the tension has reached the maximum tension.

The actual compressive force to the intervertebral disc is reasonably expected to exist between the low-risk result and the high-risk result.

IV. CONCLUSION

In this report, we proposed a method for evaluating joint reaction forces using a musculoskeletal model, and estimated the load on the intervertebral disc during lifting motion as an application example.

While minimization of the sum of squares of muscle tension or minimization of cubic sum are commonly used in muscle tension estimation, the load estimation based on such a simulation may underestimate the risk to the intervertebral disc. In this research, a new analysis method was proposed that can estimate the maximum load on the selected joints. This approach benefits from the advantage of the musculoskeletal model with polyarticular antagonistic muscles that can perform the optimization by using an additional mapping matrix on the joint reaction force. The analysis results showed that the disc compressive force calculated by the proposed method exceeded the load calculated by the general method, and that the analysis can reproduce aggressive co-contraction. This method is particularly useful for risk estimation to joints. We will perform sensitivity analysis on changes in weights of the objective function and the configuration of the model as future work.

As future developments, it can be considered to implement it as a disc load estimation / visualization system by combining this method with a motion measurement system. We will also apply this method to other joints and verify the effectiveness in analysis other than the lifting motion.

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