J Electr Eng Technol Vol. 9, No. 5: 1774-1779, 2014
http://dx.doi.org/10.5370/JEET.2014.9.5.1774

ISSN(Print) 1975-0102
ISSN(Online) 2093-7423

3-D Inverse Dynamics Analysis of the Effect of Maximum Muscle Force Capacities on a Musculoskeletal System

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Abstract – It is known that muscle strength of human body can alter or deteriorate as aging. In this study, we present an inverse dynamics simulation to investigate the effect of muscle strength on performing the daily activities. A 3D musculoskeletal model developed in this study includes several segments of whole body, long and short muscles, ligaments and disc stiffness. Five daily activities such as standing, flexion, finger tip to floor, standing lift close and lifting flexed were simulated with varying the maximum muscle force capacities (MFC) of each muscle fascicles from 30 to 90 N/cm^2 with an increment of 30 N/cm^2. In the result, no solution can be obtained for finger tip to floor and lifting flexed with 30 N/cm^2. Even though the solution was available for standing lift close activity in case of 30 N/cm^2 capacity, many of muscle fascicles hit the upper bound of muscle strength which means that it is not physiologically possible to perform the acvities in reality. For lifing flexed, even the case of 60 N/cm^2 capaciy, represents the moderate healthy people, was not able to find the solutions, showing that 18 muscles among 258 muscle fascicles reached 100% of muscle capacity. The estimated results imply that people who have low muscle strength such as elders or rehabilitation patients were required higher muscle work to perform and maintain the same daily activities than healthy one.

Keywords: Inverse dynamics analysis, Human musculoskeletal system, Maximum muscle force capacity, Spine

1. Introduction

It is known that the aging is fairly related with the change of muscle architecture resulting in the decrease of muscle strength (maximum isometric contraction) [1]. This change appeared to limit the ability to perform the daily activities and was considered as a major factor to develop fragility and cause frequently falling consequences [2]. Prevention of these incidences has therefore been addressed to elderly people and the effort to measure the relationship between the reduced muscle strength and frail problems were made through measuring the conditions of muscles [3].

Muscle strengthening exercises could be recommendable alternatives for elders to recover or slow down the reduction of muscle strength as aging [4, 5]. It was reported that high intensive and large motion based exercise programs was effective and favorable on muscle strengthening [4, 5]. However, elders who have low muscle strength and patients who underwent surgeries may be limited to perform these strenuous activities. Also, those approaches were considered as questionable for the people with low muscle strength to perform the full exercise range of motion and appeared to have high possibility to experience musculoskeletal injuries due to their low quality of muscle architecture [6]. However, it was not investigated the burden on the joints and muscles depending on the muscle strength during the various activities.

Mostly, EMG (electromyography) measurement experiments have commonly executed to assess the muscle activity in the previous studies. But there are also some technical limitations to estimate the internal forces at the joint level and individual muscle activation patterns during the activities and it is difficult to measure the specific targeted muscle activities among several hundreds of muscles due to the limited number of EMG electrodes. Also it is hard to distinguish the certain muscle among superficial and deep muscles in the overlaid musculature [7, 8]. Therefore, alternative approach combining with analytical musculoskeletal models [9, 10] has been widely used to predict internal joint forces and muscle forces. This computational modeling approach can be useful to explore the area where the experimental approaches are hardly applied to quantify the internal forces and provide the detailed muscle architecture including hundreds of muscle fascicles, ligaments, segments and joints and attained the validity of the model into biomechanical studies against a series of experimental data. As the demand of muscle effort and the activation patterns to perform daily activities increase, there were no direct quantitative investigation and the possibility of musculoskeletal injuries has not been

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Received: February 21, 2014; Accepted: May 29, 2014

demonstrated yet. Therefore, the goal of this study is to investigate the effect of maximum muscle force capacity (MFC) on joint force, muscle forces and muscle activities during various postures and lifting tasks and present the information of spinal loads, muscle activities and muscle forces.

2. The Model Description

The 3-dimensional musculoskeletal model of whole-body was developed using the AnyBody Modeling System v. 4.2 (AnyBody Technology, Aalborg, Denmark). This inverse dynamics analysis software was allowed to predict the forces in a redundant system such as the musculoskeletal system in case that the motion is predetermined. The basic information of the geometry of the segments and the muscles of whole body available in the v. 1.2 repository was used and modified including additional tissue components such as short segmental muscles, ligaments, disc stiffness and facet joints.

The developed model (Fig. 1) was obtained the validity of its usage for the purpose of this study against the previous studies [9,10]. In brief, the musculoskeletal model consists of several body components: the skull, arms, legs, pelvis, and spine which are rigid bodies and connected with rigid joints. The masses and inertia properties of each body segment were applied based on the previous experimental studies [9, 11]. The spine region consists of the cervical, thoracic and lumbar spines as well as the sacrum and the cervical and thoracic spines are modeled as a single lumped segment while the lumbar spine consists of five rigid bodies. Intervertebral disc joints were modeled as rigid spherical joints which allow three rotational motions.

Long muscles, which run over the spinal curvature, were connected over several points on the segments between insertion and origin depending on the body motions. Each muscle were divided into several fascicles under its anatomical classification and the following muscle fascicles were involved in the spine: 34 longissimus, 24 iliocostalis, 22 psoas major, 10 quadratus lumbarum, 6 external oblique, 6 internal oblique, 1 rectus abdominis, 5 transversus, 18 simispinalis, 38 lumbar multifidi, 24 thoracic multifidi, 4 serratus posterior inferior, 10 latissimus dorsi, 12 interspinales, 22 intertransversarii, and 22 rotatores (Fig. 2). All muscles were represented as single force components which can exert only tensile forces [9, 10]. The muscle dynamics features such as force-length and force-velocity relationships were not considered and also no passive element properties, tendons in muscle were considered.

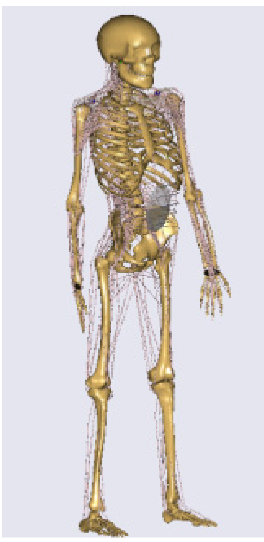

Fig. 1. A musculoskeletal model of whole body system.

Seven lumbar ligaments (anterior and posterior longitudinal, supraspinous, interspinous, intertransverse, ligamentum flavum, and capsular) were added in the lumbar spine model. Ligament forces were allowed to exert tensile force and were activated when they were stretched beyond each slack length. The nonlinearity of ligament stiffness (the load-deformation curve) was obtained from the previous experimental and analytical data [12, 13] and each ligament was calibrated and optimized for the current model [10].

The facet joints were modeled to exert contact force depending on the distance between two vertebrae. The contact point of each facet joint in vertebrae was represented as a node in the center of facet contact area on the superior and inferior articular surfaces. The nonlinear property of contact force was obtained from the previous

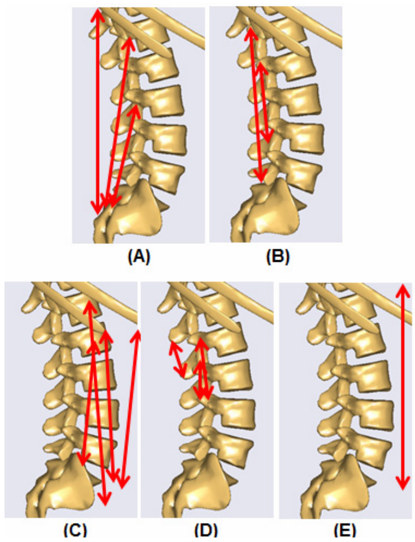

Fig. 2. Schematics of included muscles in the spine. (A) Erector Spinae; (B) Multifidi; (C) Front muscles (rectus abdominis, psoas major, quadratus lumborum, and internal and external oblique); (D) Short muscles (interspinales, intertransversarii and rotatores); (E) Rectus abdominis. Red arrows indicate the included representative muscles and their directions.

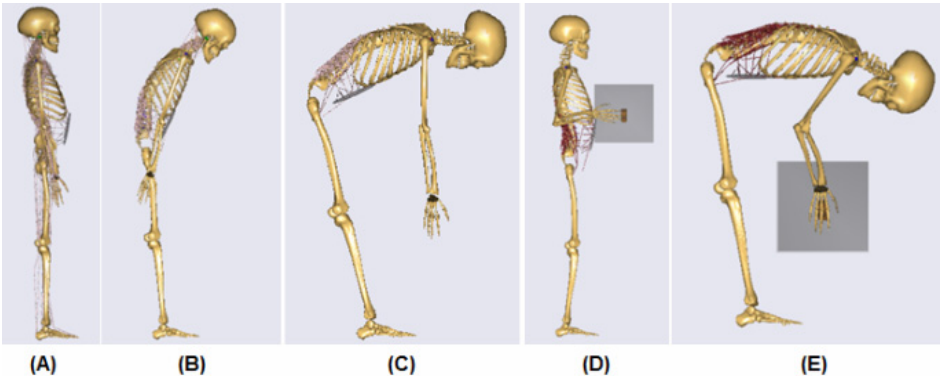

Fig. 3. Schematics of simulated activities: (A) Standing; (B) Flexion; (C) Finger tip to floor; (D) Standing lift close; (D) Lifting flexed.

study [14] and implemented into the model to be activated according to the distance between the superior and inferior articular facet nodes of the adjacent vertebrae during motions. These facet contact forces during motions were validated against the previous studies [15,16].

3. Activities Description

Schematics of simulated activities in this study are shown in Fig. 2. Five static activities considered as frequently experienced on a daily basis and assumedly lead to high loads in most muscles were chosen and modeled replicating the actual postures from a previous study [17]. The maximum muscle force capacities (MFC) of each muscle fascicles applied in the simulation were 30, 60 and 90 N/cm², presumptively representing elder or surgery patients, normal and athletes, respectively [18, 19].

4. Simulation

Muscle recruitment in inverse dynamics is the process of determining which set of muscle forces will balance a given external load. The minimum-maximum (min/max) optimization criterion built in the the AnyBody Modeling System was selected as a muscle recruitment algorithm combining with quadratic and was used to predict the joint and muscle forces and muscle activities in the spine. This optimization solver minimizes maximum muscle activation, delaying muscle fatigue and maximizing the synergy of all included muscles. In addition, muscle stress a

The final static positions of five chosen activities were simulated and analyzed by performing inverse dynamic analysis using the same software. Joint resultant forces, muscle activities and muscle forces acting on the center of each joint were calculated. The whole body model was developed to have a weight of 72 kg and a height of 1.75 m which is similar to the dimension of the subject in the previous study [17].

Muscle forces in a same category were summed, and the total force values of muscle fascicles were calculated for the presented results. For example, the 17 muscle fascicles in longissimus, running over different segments in the spine were summed regardless of their origin and insertion points.

4.1 Inverse dynamics

Inverse dynamics analyses were performed to predict spinal loads and muscle forces using the min/max and quadratic criteria in muscle recruitment using the same musculoskeletal modeling software (AnyBody Technology, Aalborg, Denmark). The details of the muscle recruitment critera were well described in the previous paper [19]. In brief, the min/max muscle recruitment criterion minimize the activation of the maximal activated muscle in the system, which lowers the maximum relative load of any muscle. This recruitment is considered as reasonable and efficient in convaying the physiological aspect of living organisms since fatigue is more likely to occur in the muscle with the maximum relative load. Hence, it would mean that the body would maximize its endurance and delay the fatigue.

The muscle recruitment solver minimizes muscle activity and muscle fatigue, thus assuming that strong muscles can do more work than weak muscles. The optimization scheme is formulated as;

$$\text{Minimize} \quad \beta + \varepsilon \sum_i \left(\frac{f_i^{(M)}}{N_i} \right)^2, \tag{1}$$

$$\text{subject to:} \quad \frac{f_i^{(M)}}{N_i} \le \beta,\ i \in \{i,..,n^{(M)}\}, \tag{2}$$

$$f_i^{(M)} \ge 0,\ i \in \{i,..,n^{(M)}\}, \tag{3}$$

$$\mathbf{Cf} = \mathbf{r}, \tag{4}$$

where, β is the muscle activity, ε is a weighting factor to include a quadratic term in the objective function (1), $f_i^{(M)}$ is the force in ith muscle, and n is the number of muscles in (2) and (3). **C** is a coefficient matrix depending

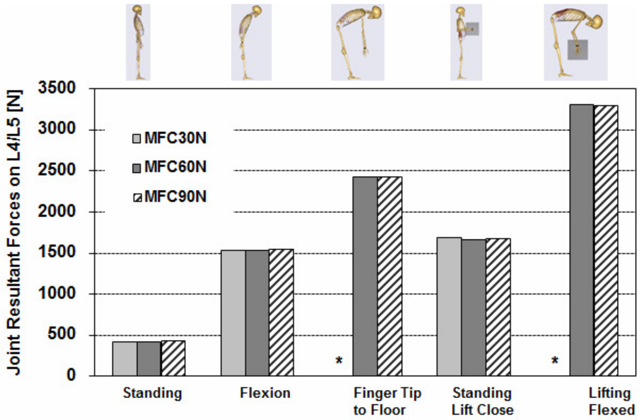

Fig. 4. Joint resultant forces at L4–L5 level computed according to the MFC variations

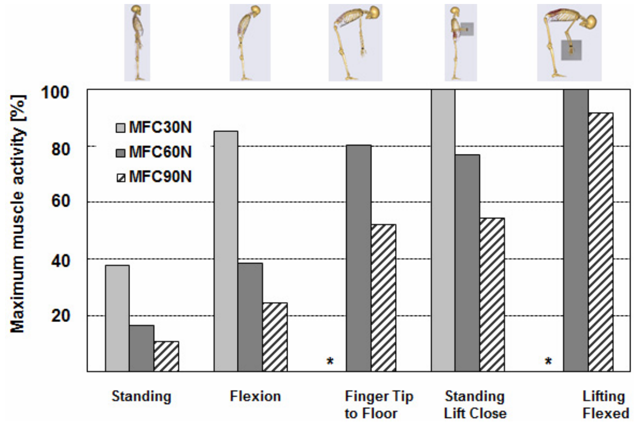

Fig. 5. Maximum muscle activity according to the MFC variations. * indicates that no solutions were available.

on the geometry and kinematics of the muscle and body segments, **f** is a vector of muscle and reaction forces to predict, and **r** is a vector of external forces and inertia forces in (4). N_i is the normalization factor which is a measure of the strength of each muscle.

The joint resultant forces on L4-L5 disc level, muscle forces and muscle activities were estimated and the total muscle forces within fascicles in same muscle categories were calculated for the result comparison.

4.2 Joint resultant forces

Generally, the trend of resultant force in all joints was increased as the motion of the trunk increase and the extra weight was imposed (Fig. 4). No considerable effect of MFCs on the joint forces was observed in all activities in case that the simulation was completed. However, larger motion activities such as finger tip to floor and lifting flexed were not simulated with the MFC of 30 N/cm². This implies that the subjects who have low muscle strength such as elders and rehabilitation patients may not be able to carry out those activities and experience abnormal loading on their spine or exposed to the spinal injuries while performing those activities.

4.3 Maximum muscle activity

In case of maximum muscle activities, as the MFCs increase from 30 to 90 N/cm², the trend of maximum muscle activities were decreased (Fig. 5). The 30 N/cm² of MFC required the most of its acvitieis to simulate the given activities and even two postures, finger top to floor and lifting tasks were not able to find the solutions with that MFC. In general, lumbar and thoracic in multifidi muscle group and longissimus and iliocostalis in erector spinae muscle group played a major role to stabilize the spine structure during all simulated postures. For example, in case of 90 N/cm², the standing posture could be achieved with only 10 % of muscle capacity of thoracic multifidi.

On the other hand, in case of 30 N/cm², 40 % of muscle capacity of thoracic multifidi was required to achieve the same postures.

4.4 Individual muscle activities

Representative maximum muscle activities among major involved muscles were given in Table 1. For flexion, the activity could be achieved with only 24 % of muscle capacity of lumbar multifidi with the MFC of 90 N/cm². In contrast, in case of 30 N/cm², 85 % of muscle capacity of lumbar multifidi was required to achieve the same postures. Similar strend was observed in longissimus msucles. This implies that persons who have low muscle strength are supposed to utilize the most of their muscle strength only to perform the normal activities which can be frequently performed and therefore they have high possibility of experiencing injuries with adding other weights or further

Table 1. Representative maximum muscle activities among majorly involved muscles were given. Predicted maximum muscle activities in % for each activity. The abbreviation of muscle names indicates: Ic = Iliocostalis; Lg = Longissimus; Ss = Semispinalis; LM=Lumbar multifidus; TM=Thracic multifidus.

Positions	MFCs	Ic	Lg	Ss	LM	TM
Standing	MFC 30N	0	0.38	0.38	0.38	0.23
	MFC 60N	0	0.17	0.17	0.17	0.13
	MFC 90N	0	0.1	0.1	0.1	0.09
Flexion	MFC 30N	0.69	0.85	0.32	0.85	0.23
	MFC 60N	0.34	0.38	0.17	0.38	0.13
	MFC 90N	0.23	0.24	0.12	0.24	0.09
Finger tip to floor	MFC 30N	-	-	-	-	-
	MFC 60N	0.69	0.8	0.25	0.8	0.13
	MFC 90N	0.46	0.52	0.17	0.52	0.09
Standing lift	MFC 30N	1	1	1	1	1
	MFC 60N	0.68	0.77	0.75	0.77	0.42
	MFC 90N	0.44	0.51	0.5	0.53	0.28
Lifting flexed	MFC 30N	-	-	-	-	-
	MFC 60N	1	1	0.32	1	0.19
	MFC 90N	0.7	0.82	0.18	0.85	0.11

Table 2. Representative muscle force values were given. Predicted muscle forces in N for each activity. Sum of forces in each muscle group was used in this comparison. The abbreviation of muscle names indicates: Ic=Iliocostalis; Lg=Longissimus; Ss= Semispinalis; LM = Lumbar multifidus; TM = Thracic multifidus.

Positions	MFCs	Ic	Lg	Ss	LM	TM
Standing	MFC 30N	12	31	57	19	23
	MFC 60N	13	30	56	19	24
	MFC 90N	13	30	55	19	26
Flexion	MFC 30N	171	208	31	55	14
	MFC 60N	174	204	32	56	15
	MFC 90N	174	202	33	57	16
Finger tip to floor	MFC 30N	-	-	-	-	-
	MFC 60N	414	470	47	110	19
	MFC 90N	414	469	49	110	20
Standing lift	MFC 30N	269	374	189	72	121
	MFC 60N	204	444	182	69	76
	MFC 90N	195	450	179	70	75
Lifting flexed	MFC 30N	-	-	-	-	-
	MFC 60N	634	779	65	231	28
	MFC 90N	695	755	60	199	23

motions during their daily lives.

Even though solutions were available for standing lift close activity in case of 30 N/cm² capacity, a number of muscles (39 among 258 muscle fascicles in the spine) hit the upper bound of muscle strengths. This means that it is not physiologically possible to perform the acvities in reality with 30 N/cm² of MFC. For lifing flexed, even the case of 60 N/cm² capacity, represents the moderate healthy people, was not able to find the solutions, showing that 18 muscles among 258 muscle fascicles reached 100% of muscle capacity. Therefore, these activities may induce high possibility of experiencing injuries to elders as well as normal peoples.

4.5 Muscle forces

In case of muscle forces, representative muscles in stabilizing the spine structure during the activities were given in Table 2. No considerable differences in muscle force values were estimated for each activity except standing lift. This implies that the similar force magnitudes were required to achieve the balance of the body structure during the simulated activities regardless of MFCs variation and only the force values change (different muscle recruitment patterns) in case that the required muscle forces exceeded the upper bound of muscle strength.

4.6 Limitations

This study has limitations in several respects though the previously validated musculoskeletal model has been used. Validation of muscle forces and their activation patterns were partially done, due to the lack of experimental data and the limitation of EMG measurement technology. Also, the model was developed considering the general body parameters and representing a single subject in the previous study. The detailed model of musculoskeletal system was used this study but is still a simplified spine model under the assumptions and a chosen specific optimization criterion. Therefore, other values of joint and muscle forces can be differed, under different optimization criteria. However, the result analysis in this study was performed by comparing the trends of the loadings in the spine muscles and joints rather than the absolute values of forces. Therefore, the approaches in this study could provide a scientifically reasonable meaning to achieve the goal and to gain confidence in the results.

5. Conclusion

In this paper, an inverse dynamics simulation using a 3D musculoskeletal model was presented to investigate the effect of muscle strength on performing the daily activities. The estimated results imply that people who have low muscle strength such as elders or rehabilitation patients required higher muscle work to perform and maintain the same daily activities than healthy one. Even large motion-driven activities such as finger tip to floor and lifting flexed postures and lifting tasks were not possible to find the solutions, optimized muscle recruitment patterns with low muscle capacities (30-60 N/cm²). Therefore, performing extreme bending exercises and lifting tasks may induce higher possibility of the incidence of injuries in the musculoskeletal systems of elderly people and surgery patients. Maximum muscle capacity can change due to several reasons such as pathological issues or sedentary life styles. These conditions may cause abnormal muscle forces and activation patterns, resulting in low back pain in daily activities. The results in this study show insight on spinal loads and muscle forces in cases with the altered muscle capacities. As a rehabilitation implication, static or isometric muscle exercises rather than large motion-driven exercises can be recommendable for elderly people and rehabilitation patients with low muscle strength.

Acknowledgements

‘The present research was conducted by the research fund of Dankook University in 2012'

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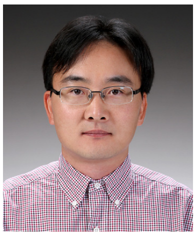

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