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Quantification Model for Muscular Forces and Momentums in Human Lower Extremities

Davor Mijatović[1], Krešimir Bulić[1] and Vasilije Nikolić[2]

[1] Department of Plastic Surgery, Universitiy Hospital Zagreb, Zagreb, Croatia
[2] Department of Anatomy »Drago Perović«, School of Medicine, University of Zagreb, Zagreb, Croatia

A B S T R A C T

The possibility of calculating muscular forces and momentums and their influence on skeleton was evaluated in this study by means of computerized tomography performed on a living person. Through this, the surface and corrected surface for each muscle cross section area were obtained, the distance from muscular centroide to the neutral bone axis was measured, and muscular force and muscular momentum on the bone were determined. Muscular momentum on the bone was obtained by multiplication of the muscular force and the distance between muscular centroide and neutral bone axis. The use of computerized tomography, as a method for creating a model for quantification of muscular forces and momentum, was proven to be reliable according to exactness in evaluation of all human lower extremity structures which is the basis for muscular biomechanical characteristic calculations.

***Key words**: lower extremity biomechanics, muscular forces, muscular momentums*

Introduction

Evolution of the mankind, posing ever increasing demands on the human locomotor system, prompted a great number of biomechanical studies in the area of various components of the locomotor system[1,2]. Abundant research in this area most often analyzes separately isolated problems or isolated segments or components of the extremities such as bones, joints or muscles, while the integral data on analysis of passive and active parts of the human locomotor system are rarely found[3–8]. Separate observation of different components can't provide a comprehensive analysis because of the close interaction and dependence of various components and associated systems. The fact that the whole organism interacts to mechanical forces and that there is interdependence between the magnitude and method of action of these forces and the organism is best shown in the supportive tissue, bone and muscle reaction to the change in mechanical load[9,10]. Bone adapts to the mechanical load by adaptation of shape, rearrangement of the inner structure and redistribution of the structural material[10]. Muscles undergo hyper or hypotrophy parallel to the change in the proportion of different muscle fiber types. Important changes also occur in the tendons, ligaments and joint capsule. All of this applies when the magnitude of applied force is within a physiologically acceptable range, while the forces of a too great intensity will lead to tissue damage or destruction[10–12]. The basic function of the locomotor system is providing mechanical support to the organism, enabling movement and providing resistance and protection from the external forces. All these functions are maintained by the maximal adaptation of the locomotor system with the minimum materials employed, in accordance to the Roux's minimum-maximum principle[13,14].

Load distribution within the skeleton is a result of action of gravitational and other active and passive forces that have a direct force load on the skeleton, with different intensities and directions[14–16]. For a comprehensive understanding of kinematics and dynamics of motion, which includes the analysis of muscular forces in motion, it is important to bear in mind that the muscular forces act on bones and joints through pull, push and torque momentums with specific geometrical relationships between the muscle, bone and joint that results in three dimensional motion[14–16]. The magnitude of the muscular force is proportional to its cross sectional surface area, that is to the sum of the muscle fiber cross section area perpendicular to their axis[17–19]. Although we can estimate the activity of each muscle and forces in various

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joints in vivo through electromyography, dynamometry, and special force measuring platforms and through kinematical and dynamical analysis of various referral points marking specific body segments recorded by video cameras, the exact magnitude of muscular forces and geometrical properties of each muscle is very hard to determine[17–21]. This especially applies in pathological conditions, where the problem of exact quantification of muscular forces and momentums is of paramount importance in determining the appropriate treatment modality[17–21]. Having in mind the variation in forces within the locomotor system, as well as within the skeleton and muscular system, there is a justification and a necessity in an attempt to determine biomechanical properties in extremities through determination of muscular forces and momentums which would enable objective visualization based on computerized analysis of the data that can be obtained in a direct or indirect manner[17–21].

Material and Methods

The study was conducted at the Department of Anatomy Drago Perović, University of Zagreb, School of Medicine and at Department of Radiology, University Hospital »Sestre Milosrdnice« Zagreb. Subject of the investigation was the author of this article, male, age 35, 175 cm high. The thigh and the lower leg of the subject were scanned by computerized tomography, Siemens Somatom DR. Adequate radiation protection was used for the rest of the body. CT scan was done on the midpoint of the thigh, determined by measuring the distance between the mayor trochanter of the femur and genicular articular line, and on the midpoint of the lower leg, determined by measuring the distance between genicular articular line and medial tibial maleole.

Measurements of surfaces for each muscle and the distance between each muscle centroid and neutral bone axis were done on millimeter grid paper after copying the CT cross-section scans.

The origin of the coordinate system for particular bone cross section goes through the neutral axis of the bone (femur, tibia, and fibula). Muscular surface on CT scan, that is, on millimeter grid paper, was measured by use of planimetric method and divided with picture correction factor for getting the real surface value.

Surface and corrected surface for each muscle on the thigh and the lower leg was calculated as well as the distance between neutral bone axis and each thigh (fig.1) and lower leg (fig. 2) muscle centroid. In muscle force calculation we used, in literature known maximum, medium and the lowest force values of 30 N/cm^2, 60 N/cm^2 and 90 N/cm^2. The distance between bone centroid and muscle centroid was taken for determination of the momentum leaver. Muscular momentums on the bone were calculated as multiplication of muscle force and the distance of bone centroid which give us the moment of particular muscle on the bone in Nm. The similar method was used by McGill.

Results

Muscle cross-section surface and their distances from neutral bone axis

The surfaces and corrected surfaces of muscles cross-section shown on CT scans and the distance between neutral bone axes and muscle centroid in each thigh and lower leg muscle measured at the midpoint are shown in Tables 1 and 2.

The forces in each thigh and lower leg muscle are shown in Tables 3 and 4. In force calculations, we have used three variants for muscle force calculation – 30, 60 and 90 Ncm^{-2}

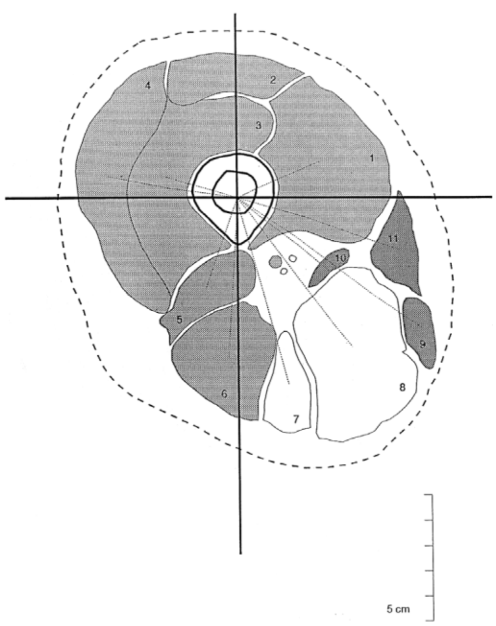

Fig. 1. Cross section through the right thigh.

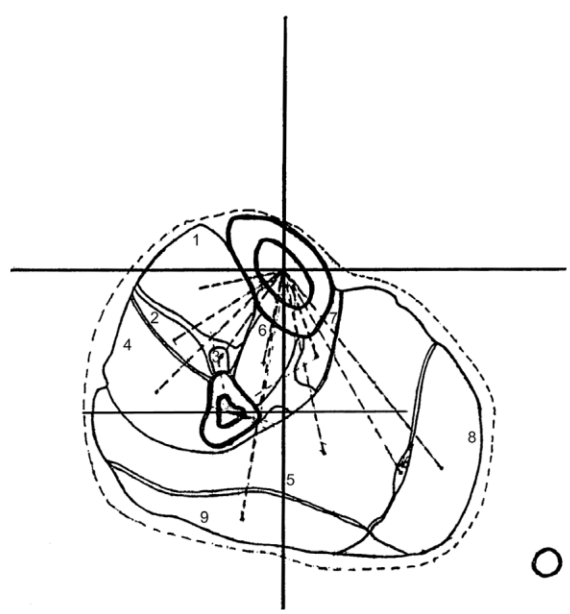

Fig. 2. Cross section through the right lower leg.

TABLE 1
RIGHT AND LEFT THIGH MUSCLE CROSS SECTION SURFACE AREA, CORRECTED AREA AND DISTANCE FROM THE FEMUR NEUTRAL AXIS

	Right thigh			Left thigh		
Muscle	Area (cm^2)	Corrected area (cm^2)	Distance from femur neutral axis (cm)	Area (cm^2)	Corrected area (cm^2)	Distance from femur neutral axis (cm)
M. vastus medialis	7.23	14.75	2.2	7.13	14.55	2.4
M. rectus femoris	1.52	3.10	3.0	1.62	3.30	3.0
M. vastus intermedius	6.48	13.22	1.8	6.39	13.04	1.6
M. vastus lateralis	4.75	9.69	3.2	4.81	9.81	3.1
M. biceps femoris (caput breve)	1.77	3.61	2.4	1.75	3.57	2.2
M. biceps femoris (caput longum)	3.85	7.85	4.0	3.88	7.91	4.0
M. semitendinosus	1.79	3.65	4.8	1.76	3.59	4.9
M. semimembranosus	3.98	8.12	4.6	3.90	7.95	4.8
M. gracilis	1.31	2.67	5.6	1.36	2.77	5.7
M. adductor magnus	0.39	0.79	2.8	0.38	0.77	3.0
M. sartorius	1.58	3.22	4.2	1.51	3.08	4.5

TABLE 2
RIGHT AND LEFT LOWER LEG MUSCLE CROSS SECTION SURFACE AREA, CORRECTED AREA AND DISTANCE FROM THE TIBIA AND THE FIBULA NEUTRAL AXIS

	Right lower leg				Left lower leg			
Muscle	Area (cm^2)	Corrected area (cm^2)	Distance from tibial neutral axis (cm)	Distance from fibular neutral axis (cm)	Area (cm^2)	Corrected area (cm^2)	Distance from tibial neutral axis (cm)	Distance from fibular neutral axis (cm)
M. tibialis anterior	3.00	8.33	1.9	2.2	3.17	8.80	2.20	2.2
M. extensor digitorum longus	1.03	2.86	2.9	1.4	1.11	3.08	3.0	1.4
M. extensor hallucis longus	0.22	0.61	2.3	0.8	0.20	0.55	2.5	0.9
M. fibularis longus	1.80	5.00	3.5	1.3	1.76	4.88	3.6	1.1
M. soleus	7.00	19.44	2.9	2.9	6.88	19.11	3.3	3.1
M. tibialis posterior	1.62	4.50	1.6	1.4	1.60	4.44	1.7	1.3
M. flexor digitorum longus	1.21	3.36	1.4	2.7	1.18	3.27	1.6	2.7
M. gastrocnemius (c.mediale)	5.00	13.88	4.6	5.0	5.09	14.13	5.1	5.2
M. gastrocnemius (c.laterale)	3.96	11.0	4.1	1.6	4.00	11.11	4.2	1.6
M. plantaris	0.16	0.44	3.5	4.1	0.15	0.41	4.1	4.5

Muscular forces and momentums

Muscular momentums on femur in right and left tight are shown in Table 5.

The greatest momentum on femur have m. vastus medialis and m. vastus lateralis as the extensor muscles, and m. biceps femoris (caput longum) as the flexor muscle.

M. soleus and m. gastrocnemius have the greatest momentum on tibia (Table 6) and fibula (Table 7) and extensor muscles, m. tibialis anterior and m. fibularis longus, have the greatest moment on leg bones. The difference between medial and lateral head of gastrocnemius muscle is so small that it can be ignored.

Results also show the existence of a near balance between flexor and extensor muscles, but leg extensors (the muscles of anterior leg), also like plantar flexors (the muscles of posterior part of the leg), have some greater muscular moment. That is in accord with a well known clinical fact such is extremity position in tetania (tetanus, hypoclaciemia, decerebration rigidity).

Discusion

The forces produced by muscles can cause various movements without resistance but they can also maintain static balance in certain position as well as dynamic balance during body movement, or enable lifting and transport of weight[1–6]. Muscular contraction can be realized as isotonic, with increasing or constant force or iso-

TABLE 3
RIGHT AND LEFT THIGH MUSCULAR FORCES CALCULATIONS

Right thigh				Left thigh			
Corrected area (cm^2)	Muscle force (n) 30	Muscle force (n) 60	Muscle force (n) 90	Corrected area (cm^2)	Muscle force (n) 30	Muscle force (n) 60	Muscle force (n) 90
14.75	442.5	885.0	1327.5	14.55	436.5	873.0	1309.5
3.10	93.0	186.0	279.0	3.30	99.0	189.0	297.0
13.22	396.6	793.2	1189.8	13.04	391.2	782.4	1173.6
9.69	270.7	581.4	872.1	9.81	294.3	588.6	882.9
3.61	108.3	216.6	324.9	3.57	107.1	214.2	321.3
7.85	235.5	471.0	706.5	7.91	237.3	474.6	711.9
3.65	109.5	219.0	328.5	3.59	107.7	215.4	323.1
8.12	243.6	487.2	730.8	7.95	238.5	477.0	715.5
2.67	80.1	160.2	240.3	2.77	83.1	166.2	249.3
0.79	23.7	47.4	71.1	0.77	23.1	46.2	69.3
3.22	96.6	193.2	289.8	3.08	92.4	184.8	277.2

TABLE 4
RIGHT AND LEFT LOWER LEG MUSCULAR FORCES CALCULATIONS

Right lower leg				Left lower leg			
Corrected area (cm^2)	Muscle force (n) 30	Muscle force (n) 60	Muscle force (n) 90	Corrected area (cm^2)	Muscle force (n) 30	Muscle force (n) 60	Muscle force (n) 90
8.33	249.9	499.8	749.7	8.80	264.0	528.0	792.0
2.86	85.8	171.6	257.4	3.08	92.4	184.8	277.2
0.61	18.3	36.6	54.9	0.55	16.5	33.0	49.5
5.00	150.0	300.0	450.0	4.88	146.4	292.8	439.2
19.44	583.2	1166.4	1749.6	19.11	573.3	1146.6	1719.9
4.50	135.0	270.0	405.0	4.44	133.2	266.4	399.6
3.36	100.8	201.6	302.4	3.27	98.1	196.2	294.3
31.88	416.4	832.8	1249.2	14.13	423.9	847.8	1271.7
11.00	330.0	660.0	990.0	11.11	333.3	666.6	999.9
0.44	13.2	26.4	39.6	0.41	12.3	24.6	36.9

metric contraction which is realized without movement, that is, without muscle fibers shortening but with tension increasing[6–9]. In both cases, the energy source is the chemical energy utilized by muscles and transformed into mechanical energy (elastic, potential, kinetic), and heat[6–9].

In our study we have used computer tomography imaging for muscle analysis.

Muscle surface shown on CT is not representing physiological cross-section of muscle. This surface is corrected surface, that is, real picture of horizontal muscle cross-section in particular CT cross section[10–13]. In muscles with longitudinal fibers, corrected surface is taken by measuring the cross section of the muscle in particular segment[14–16]. In feather-like muscles we have used Fick relation – when the muscular forces are at an angle with the tendon axis, tracking muscle force (Fm) will produce in tendon force component (Ft) depending on angle:

$$\cos \alpha = Ft/Fm$$

During the contraction the angle is changing. In feather-like muscles, fibers are running form their bone origin (length L) towards the tendon in a maximally short distance (a) muscle fibers layer thickness (b) fiber length in relaxed condition (l) and muscle fibers length in contraction (Δl)(14–16). The muscle fibers angle near tendon in relaxed condition (α) is changing during the contraction in angle ($\alpha 1$). During that, muscle fibers are contracting by contraction quotient $Cs = \Delta l/l$ into new length $l1 = l - \Delta l$, that is, by Alexander

$$l1x \sin \alpha 1 = a$$

$$\sin \alpha 1 = \sin \alpha / Cs$$

that is,

$$\cos \alpha 1 = (Cs - \sin \alpha)^{1/2}/Cs$$

TABLE 5
MUSCULAR MOMENTUMS ON THE RIGHT AND LEFT FEMUR

Muscle	Momentum on rifgt femur (nm)			Momentum on left femur (nm)		
	30	60	90	30	60	90
M. vastus medialis	9.75	19.47	29.20	10.47	20.95	31.42
M. rectus femoris	2.80	5.58	8.37	2.97	5.94	8.91
M. vastus intermedius	7.14	14.27	21.41	6.25	12.51	19.58
M. vastus lateralis	9.30	18.60	27.90	9.12	18.25	27.37
M. biceps femoris (caput breve)	2.60	5.19	7.79	2.35	4.72	7.10
M. biceps femoris (caput longum)	9.42	18.84	28.26	9.50	18.98	28.74
M. semitendinosus	5.26	10.51	15.76	5.27	10.55	15.73
M. semimembranosus	11.20	22.41	33.61	11.44	22.89	34.34
M. gracilis	4.48	8.97	13.45	4.73	9.47	14.21
M. adductor magnus	0.66	1.33	1.99	0.69	1.38	2.07
M. sartorius	4.05	8.11	12.17	4.15	8.31	12.47

TABLE 6
MUSCULAR MOMENTUMS ON THE RIGHT AND LEFT TIBIA

Muscle	Momentum on right tibia (nm)			Momentum on left tibia (nm)		
	30	60	90	30	60	90
M. tibialis anterior	4.74	9.50	14.24	5.28	10.56	15.84
M. extensor digitorum longus	2.48	4.97	7.46	2.77	5.54	8.31
M. extensor hallucis longus	0.42	0.84	1.26	0.41	0.82	1.23
M. fibularis longus	5.25	10.50	15.75	5.27	10.54	15.81
M. soleus	16.91	33.82	50.73	18.91	37.83	56.75
M. tibialis posterior	2.16	4.32	6.48	2.26	4.52	6.79
M. flexor digitorum longus	1.41	2.82	4.23	1.56	3.13	4.22
M. gastrocnemius (c.mediale)	19.15	38.30	57.46	21.61	43.23	64.85
M. gastrocnemius (c.laterale)	13.53	27.06	40.59	13.99	27.99	41.99
M. plantaris	0.42	0.92	1.38	0.50	1.00	1.51

The total muscle fibers volume $Vm = a \times b \times L$, physiological cross-section $A1 = b \times L$, the number of muscle fibers $bL/(axsin\alpha)$, vertical force in the tendon will respond to:

$$Ft = Fmcos\ \alpha 1$$

Ratio between vertical force caused by feather-like muscles and the vertical force of same volume muscle with parallel fibers can be lager or smaller than 1 which depends on the angle[14–16].

Our study model on human lower extremities introduce computerized tomography as a method for determination of muscular forces and momentums. Therefore, it is necessary to emphasize following details which are, by our opinion crucial understanding the procedure:

- the muscular momentums and estimated muscular forces which are acting on bones, shown in our results, are related only to analysis of investigated muscle cross-section,
- corrected surface which we have used in further calculation is not a physiological cross-section,
- calculated relations of muscular momentums are representing the condition of tension in particular cross-section and influence on bone segment in particular bone cross section,
- when the bone is intact, muscular forces are participating in dynamic modeling tension distribution of bone cross-section,
- the computerized tomography layers above and below the particular cross-section could enable more accurate analysis of muscle influence on bone,
- this study model is not related to muscle influence on joints because of need for serial CT analysis below and above muscle attachment, including the joints themselves,
- computerized tomography in this study model was performed with patient in supine position, with extremities in extension, foot in neutral position and relaxed muscles.

TABLE 7
MUSCULAR MOMENTUMS ON THE RIGHT AND LEFT FIBULA

Muscle	Momentum on right fibula (nm)			Momentum on left fibula (nm)		
	30	60	90	30	60	90
M. tibialis anterior	5.49	10.99	16.49	5.80	11.61	17.42
M. extensor digitorum longus	1.20	2.40	3.60	1.29	2.58	3.88
M. extensor hallucis longus	0.14	0.29	0.43	0.14	0.29	0.44
M. fibularis longus	1.95	3.90	5.85	1.61	3.22	4.83
M. soleus	16.91	33.82	50.73	17.77	35.54	53.31
M. tibialis posterior	1.89	3.78	5.67	1.73	3.46	5.19
M. gastrocnemius (c.mediale)	20.82	41.64	62.46	22.04	44.08	66.12
M. gastrocnemius (c.laterale)	5.28	10.56	15.84	5.33	10.66	15.99
M. plantaris	0.54	1.08	1.62	0.55	1.10	1.66

Serial computerized tomography of extremities could give us more accurate biomechanical analysis, especially with muscles in relaxed and contracted condition[17,18]. But for such analysis it will be required to perform additional CT scans what will cause high amount of x-ray emission which is ethically not acceptable[17,18].

Nevertheless, additional important data can be given by use of ultrasound like Ikai and Fukunaga in their investigation[19].

Ultrasound echography in some transverse and longitudinal cross-sections can define surface relation and volume of particular muscles as well as their direction.

Ultrasound echography can present real time situation which means muscles in relaxed and contracted condition an moment of contraction[19–21].

Furthermore, it enables serial cross-section analysis of muscle through longitudinal axis like on CT but without negative effects of irradiation[19–21].

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D. Mijatović

Department of Plastic Surgery, University Hospital Center »Zagreb«, Kišpatićeva 12, 10000 Zagreb, Croatia
e-mail: plasurg@kbc-zagreb.hr

MODEL KVANTIFIKACIJE MIŠIĆNIH SILA I MOMENATA U DONJIM EKSTREMITETIMA ČOVJEKA

S A Ž E T A K

U ovom istraživanju je evaluirana mogućnost za izračun rasporeda sila i momenata djelovanja mišića na skelet u živa čovjeka primjenom kompjutorizirane tomografije. Na ovaj način, određena je za svaki mišić površina i korigirana površina kako bi se dobila realna vrijednost površine, zatim udaljenost od centroida mišića do neutralne osi kosti, snage mišića te moment djelovanja na kost. Moment djelovanja mišića dobiven je množenjem sile mišića i udaljenosti centroida od neutralne osi kosti. Upotreba kompjutorizirane tomografije, kao metode za stvaranje modela za kvantifikaciju mišićnih sila i momenata, se pokazala pouzdanom zbog preciznosti u evaluaciji svih struktura donjih ekstremiteta u čovjeka, što je osnova za izračun biomehaničkih karakteristika.