Joint Torque Modeling of Knee Extension and Flexion

Fabian Guenzkofer, Florian Engstler, Heiner Bubb, and Klaus Bengler

Institute of Ergonomics, Technische Universität München,
Boltzmannstr.15, 85747 Garching, Germany
{guenzkofer,engstler,bengler,bubb}@lfe.mw.tum.de

Abstract. The purpose of this experiment is to obtain isometric knee extension and flexion joint torque - joint angle functions considering necessary biomechanical aspects. In order to examine gender and age effects four different subject groups (10 young males and females, 8 old males and females) were used. Age and gender had a significant influence for both force directions. Not only different maximum values but also different curve shapes were identified for different age groups. Additionally the hip flexion angle significantly influenced the joint torque production.

Keywords: joint torque, age effects, strength, knee, force.

1 Introduction

Knowledge of executable forces in different postures is crucial for product design [1] as well as for workplace design [2]. Strength prediction for arbitrary postures presupposes correlations between joint angles and joint torques [3] due to the length – tension relationship of muscles [4]. Furthermore torque-angle curves permit posture prediction by a minimization of all joint torques [5]. From all relevant torque – angle relationships this paper concentrates on the relationships in isometric knee extension and knee flexion.

Several authors have examined the variation of knee flexion torque within the range of knee flexion motion keeping the hip flexion angle constant [6-10]. All studies revealed a descending curve. However, taking into account the responsible muscles indicates that hereby an important aspect is neglected:

The biggest muscles responsible for the knee flexion are the m. biceps femoris, the m. semitendinosus and the m. semimembranosus. Except the short head of the m. biceps femoris all muscles are biarticular. That is to say, they cover the knee as well as the hip joint. Therefore the position and posture of the hip should have a distinct influence on the maximum joint torque of knee flexion. Some authors have considered this interrelation and have additionally varied the hip flexion angle [11-13]. All of them state that the joint torques significantly increased with the hip being more flexed.

In her review of human strength curves Kulig [14] mentions knee extension measurements by only varying the knee flexion angle [15-16]. Several more authors examined knee extension joint torque – knee joint angle relationship [7-9, 10, 17, 18].

V.G. Duffy (Ed.): Digital Human Modeling, HCII 2011, LNCS 6777, pp. 79–88, 2011.

In some cases the hip flexion angle was not controlled as no backrest was available for the subjects [16, 19]. In almost all of these studies the researchers were faced with an ascending limb, followed by a plateau and finally by a descending limb.

Regarding knee extension the m. rectus femoris is the only biarticular muscle. Herzog et al. [20] compared knee extensor strength curves with two different hip flexion angles obtained theoretically and experimentally. They hypothesized an offset between the strength curves with a right shift of higher hip flexion angles (seated instead of prone). The results agreed well with each other. Also Houtz et al. [11] examined the influence of varied hip flexion angles on knee extension torque and was faced with a shift due to hip flexion angle.

Another important aspect for product and workplace design is the loss of strength due to aging [10, 21-24]. Some authors have compared strength differences between young and old subjects [19, 27]. Samuel et al. [10] have compared knee joint torques of 60-, 70- and 80-year-old subjects. The 80-year old subjects had 20% less strength compared to the 60-year-olds. In this study women produced approximately 40% less knee torques than men.

In the context of the research project DHErgo functional joint torque data are collected for digital human models. In comparison to most studies which solely concentrate on particular joints, complete individual torque models of the subjects should be developed by comprehensive torque measurements combining all relevant degrees of freedom and adjacent joints. To account for the low sample size, the idea is to combine these detailed measurements with a large database of strength data in order to obtain percentile values for joint torques [28].

This paper describes isometric knee joint torque measurements in numerous joint positions considering necessary biomechanical aspects using four different subject groups. The aim of the data collection is not to create a huge amount of data for reliable population prognosis. Taking detailed measurements on 18 subjects should reveal qualitative information about general curve shapes and influences of adjacent joint angles.

2 Methods and Materials

2.1 Subjects

Eighteen subjects volunteered to take part in this study. In order to be able to examine age and gender effects young and old as well as female and male subjects were recruited (see table 1). Age group definitions were agreed on within the DHErgo consortium. All subjects had to fulfill specific requirements. On the one hand competitive athletes were rejected as the results should approximate average population strengths at the best. On the other hand subjects had to be healthy and free of orthopaedic and neurological disorders. All subjects gave their written consent after having been informed about the purpose of the study and its procedures.

Table 1. Mean and standard deviation of age, height and weight of subjects in each group

Group	N	Age	Height	Weight
Young men	5	30,2 ± 2,95 years	180,67 ± 4,03cm	77,96 ± 11,11 kg
Young women	5	24,2 ± 4,32 years	165,68 ± 2,42 cm	57,28 ± 4,76 kg
Old men	4	75,5 ± 3,11 years	172 ± 3,34 cm	81,03 ± 3,98 kg
Old women	4	73,25 ± 5,44 years	162,4 ± 3,47 cm	67,43 ± 8,05 kg

2.2 Apparatus

Joint torques were measured using a modified training device with several adjustment possibilities (see Fig. 1). The backrest can be adjusted in height and inclination and the distance to the seat pan can be varied to account for different thigh lengths. A burster torque sensor (burster präzisionsmesstechnik gmbh & co kg, Gernsbach, Germany) directly grabs the joint torque. Straps for the upper body ensured maximum stabilization for the subjects. The torque sensor read-out was conducted using LabVIEW 8.5 (National Instruments Corporation, Austin, USA).

Fig. 1. Adjustable knee joint torque measuring device

Postures of the subjects were recorded using the six-camera optoelectronic Vicon MX T10 motion analysis system (Oxford Metrics Ltd., Oxford, UK). However, motion reconstruction is not part of this paper. For the analysis the requested joint angles were used.

2.3 Experimental Design

In order to obtain the knee joint torque – knee flexion angle relationship dependent on different hip flexion angles both joint angles were varied for the experiment (see table 2). Unpublished pretests have shown that the differences resulting from 45 and 0 degrees (torso and thighs in line) hip flexion angles were quite negligible for knee flexion. Therefore only two different but extreme hip flexion angles (0 and 90 degrees) are taken into account. In order to best obtain the course of the function four different knee flexion angles are used. A knee flexion angle of 0 degrees means full extension. Furthermore unpublished pretests have revealed that ascending and descending limbs of knee extension were almost linear with a maximum at 60 degrees independent from the hip flexion angle. Therefore only three different knee flexion angles have been chosen. A knee flexion angle of 60 degrees was only combined with one hip flexion angle.

Table 1. Measurement positions for the experiment

Position	Hip flexion angle	Knee flexion angle	Position	Direction
1	0	0	Prone	Flexion
2	0	30	Prone	Flexion
3	0	60	Prone	Flexion
4	0	110	Prone	Flexion
5	90	0	Seated	Flexion
6	90	30	Seated	Flexion
7	90	60	Seated	Flexion
8	90	110	Seated	Flexion
9	0	20	Supine	Extension
10	0	110	Supine	Extension
11	45	20	Seated	Extension
12	45	60	Seated	Extension
13	45	110	Seated	Extension
14	90	20	Seated	Extension
15	90	110	Seated	Extension

For the isometric joint torque measurements the plateau-method was used, in which the subjects build up their maximum force in the first second and maintain the force for four seconds [29-32]. The average value over a three seconds interval during the last four seconds matches the maximum value. In between two trials the subjects had a rest period of 2 minutes. In order to ensure getting the real maximum torque value the subjects performed two trials in every position. Throughout the experiment the subjects didn´t receive any kind of motivation, neither verbal encouragement nor visual feedback [29, 30].

2.4 Procedure

Each subject was instructed on the experimental procedure and some anthropometrical measures were taken. After the possibility to pose questions they ran through a warm-up phase consisting of 15 minutes on a cross-trainer and 10 squats. The subjects were then familiarized with the measuring device. The device was adjusted to their anthropometric dimensions. The right lateral femoral epicondyle was used for the correct alignment of the anatomical flexion and the sensor axis. By means of a goniometer the different knee flexion and hip flexion angles were each set. Thereupon the subjects had the possibility to perform training trials to get used to the measurement positions and the strategy to optimally apply the maximum possible force. After performing the maximum torque measurements the subject´s lower leg was tied to the bolster and the subject had to relax. Thus the torque induced by the body segment weight was recorded in order to take into account gravitational influences.

2.5 Data Analysis

All data were analyzed using the SPSS statistical package, release 18 (SPSS, Inc., Chicago, IL, USA). Of the two repetitions per trial only the higher value was further processed [29]. The level of statistical significance was set at $p<.05$. A mixed design ANOVA was conducted using age and gender as between-subjects factors and hip and knee as repeated-measures within-subject variables. Non-linear multiple regression analyses were performed using Matlab R2009a (Mathworks, Inc., Natick, MA, USA).

3 Results

The resulting joint torques for each group are listed up in table 3.

Table 2. Mean and standard deviation of resulting joint torques for each group

			Men				Women			
			Young		Old		Young		Old	
	knee	hip	M	SD	M	SD	M	SD	M	SD
Flexion	0	0	83.78	25.64	38.10	11.89	52.84	9.10	30.23	9.64
	30	0	76.42	21.64	40.68	7.08	43.88	2.62	27.75	10.12
	60	0	71.40	15.28	38.03	6.79	35.14	5.01	22.93	9.68
	110	0	40.08	6.74	22.00	7.42	22.72	3.26	19.60	0.40
	0	90	64.34	14.91	35.15	14.48	44.62	5.08	18.90	5.21
	30	90	71.58	26.95	28.20	7.40	43.86	13.03	18.13	7.06
	60	90	73.82	16.79	28.83	9.72	49.00	9.46	18.93	7.34
	110	90	61.22	13.34	31.80	8.73	41.50	8.41	23.80	10.87
Extension	20	0	91.42	26.57	57.03	12.22	70.24	17.30	39.55	9.98
	110	0	107.66	14.83	53.48	22.25	71.56	12.57	37.98	2.90
	20	45	92.72	17.27	53.50	15.75	73.28	21.07	40.55	3.45
	60	45	131.78	25.74	72.80	17.87	101.88	16.03	45.35	11.11
	110	45	117.64	9.89	64.30	13.70	83.96	11.76	43.08	11.99
	20	90	88.12	22.58	45.48	18.64	71.34	22.61	33.43	2.95
	110	90	111.28	9.77	60.85	15.59	82.72	5.97	40.05	12.47

Joint angle – joint torque diagrams are depicted in figure 2. Standard deviations (included in table 3) are omitted in favor of clarity.

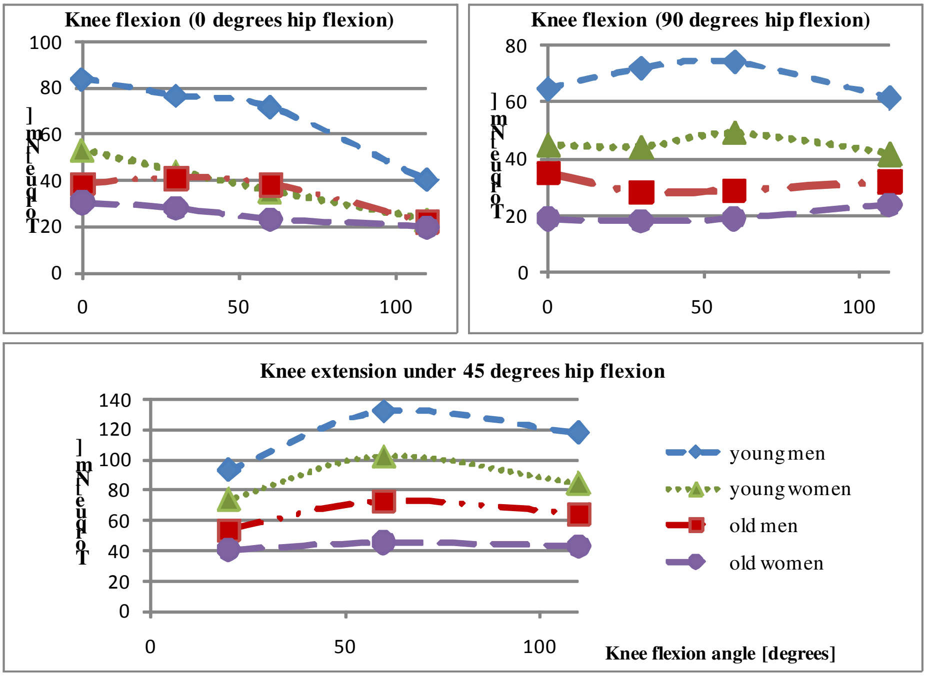

Fig. 2. Mean Torque Values for each measurement posture for each group

Knee Flexion. The main effects gender, F(1,13)=15.20, p<.01, as well as age, F(1,13)=34,67, p<.001, had a significant effect on torque production. The effect of age on torque production was not different between male and female subjects, F(1,13)=3.92, p>.05. As expected, the resulting joint torques were significantly dependent on the knee flexion angle, F(3, 39)=13.78, p<.001. Contrasts revealed that the knee flexion angle of 110 degrees significantly differs from all other knee flexion angles. The main effect hip angle did not show a significant influence, F(1,13)=.14, p>.05. However, interaction effects show, that the influence of knee angles have to be considered in context of hip position, F(3,39)=17.32, p<.001, and age, F(3,39)=4.04, p<.05. The diagrams in Figure 2 support the results from contrasts that for a hip angle of 90 degrees different knee flexion angles have only a minor effect. Adopting a hip angle of 0 degrees, increasing knee angles lead to decreasing joint torques. Concerning age, interaction graphs show that up to 60 degrees knee flexion, young and old groups show parallel lines. The torque decay beyond 60 degrees is significantly higher for young subjects. At last, the way the hip angle influences the torque production in certain knee positions is again dependent on age (interaction effect knee*hip*age), F(3,39)=3.32, p<.05.

Multiple regression analyses revealed the following equations for young males (1), young females (2), old males (3) and old females (4). The variables h stand for hip flexion angle and k for knee flexion angle. In brackets two coefficients of determination are given. The first one refers to the averaged values for each groups (see table 2) and the second one for a regression using the individual values. The low amount of shared variance for the second correlation is not unexpected but due to different strengths per group.

$$T = 82.54 - 0.2008h - 0.0097k + 0.0040hk - 0.0034k^2 \ (R_1^2=.99;\ R_2^2=.35) . \quad (1)$$

$$T = 51.58 - 0.0734h - 0.2171k + 0.0028hk - 0.0005k^2 \ (R_1^2=.96;\ R_2^2=.58) . \quad (2)$$

$$T = 38.35 - 0.0383h + 0.0759k - 0.0044hk - 0.0002k^2 + 5.254e\text{-}5hk^2 - 1.693e\text{-}5k^3 \ (R_1^2=.99;\ R_2^2=.34) . \quad (3)$$

$$T = 31 - 0.1394h - 0.1658k + 0.0016hk + 0.0006k^2 \ (R_1^2=.98;\ R_2^2=.28) . \quad (4)$$

Knee Extension. Due to the results of pretests the knee flexion angle of 60 degrees was only combined with one hip flexion angle of 45 degrees. Therefore the mixed design ANOVA could only be conducted with two knee flexion angles of 20 and 110 degrees. Both knee angles lead to significantly different joint torques, $F(1,14)=7.27$, $p>.05$. Similarly to knee flexion gender, $F(1,14)=15.56$, $p>.01$, as well as age, $F(1,14)=75.77$, $p<.001$, had a significant influence. Furthermore an interaction effect of knee x hip could be detected, $F(2,28)=4.01$, $p<.05$. Contrasts revealed significant differences when comparing the torque of 0 and 45 degrees as well as 0 and 90 degrees hip flexion for both knee angles. No interaction effect between knee position and age could be identified. However, looking at Fig. 2, it becomes evident, that age influences the shape of the functions when taking a knee flexion angle of 60 degrees into account. Therefore an additional repeated-measures ANOVA with only 45 degrees hip flexion and three knee positions was conducted. Again significant influences for knee position, $F(2,28)=18.87$, $p<.001$, gender, $F(1,14)=15.03$, $p<.01$, and age, $F(1,14)=57.01$, $p<.001$, were detected. Contrasts show differences between all knee flexion angles. In this case also the interaction effect knee x age turned out to be significant, $F(2, 28)=4.25$, $p<.05$. Contrasts revealed a significantly different torque increase from 20 to 60 degrees knee flexion between the young and old groups.

Similarly to knee flexion multiple regression analyses lead to the following equations (5-8).

$$T = 55.98 + 0.1934h + 2.006k - 0.0027h^2 + 0.0009hk - 0.0139k^2 \ (R_1^2=.99;\ R_2^2=.42) . \quad (5)$$

$$T = 42.84 + 0.1943h + 1.571k - 0.0023h^2 + 0.0012hk - 0.0119k^2 \ (R_1^2=.99;\ R_2^2=.34) . \quad (6)$$

$$T = 40.89 + 0.0336h + 0.9094k - 0.0023h^2 + 0.0023hk - 0.0072k^2 \ (R_1^2=.98;\ R_2^2=.23) . \quad (7)$$

$$T = 35.85 + 0.0923h + 0.2216k - 0.0020h^2 + 0.0010hk - 0.0018k^2 \ (R_1^2=1;\ R_2^2=.17) . \quad (8)$$

4 Conclusions

The purpose of the current study was to examine joint torque – joint angle relationships for knee extension and flexion for different subject groups.

In many comparable studies knee flexion torques follow a descending limb over the range of knee motion [6-12] for a hip flexion angle of 0 degrees (prone position). This is also true for our experiments. Only old males applied less force than expected at a knee flexion angle of zero degrees. Figure 2 illustrates a correlation between slope and intercept. That is to say, strong persons show higher strength variability than weaker ones.

Some authors report that hip flexion changes the shape from descending to ascending-descending [11-13]. In our experiments this is only true for young males. Old males show a contrarian behavior. Furthermore these authors identified a torque shift induced by different hip positions. This could also be found in our experiments. Adopting a knee flexion angle of 0 degrees the subjects applied a significantly higher torque in the prone position than in the seated position. It is assumed that the increased hip flexion leads to an excess of the ideal muscle length of the hamstrings. Reversely subjects showed significantly higher torques in the seated position than in the prone position, assuming a knee flexion angle of 110 degrees. In this case further flexing the hip lengthens the hamstrings towards ideal muscle length.

It seems that the weaker the subjects are the smaller is the influence of the position in the knee range of motion for the knee flexion torque.

Knapik et al. [7] discovered that the angle at which peak torques occurred was highly variable among subjects. This can also be seen in our tests with a hip flexion angle of 90 degrees. Fig.2 shows that the occurrence of the maximum depends on the age group. The young groups have their maximum at a knee flexion of 60 degrees, old men at zero degree and old women at 110 degrees.

All reviewed papers showed ascending – (plateau) – descending shapes for knee extension [7-11, 17-20]. Houtz et al. [11] and Herzog et al. [20] report a torque shift due to changing hip flexion angles. Exactly this behavior was evident in our experiments. A hip flexion angle of zero degrees leads to higher torques at a knee flexion angle of 20 degrees than a hip flexion angle of 90 degrees. The reverse behavior is the case for a knee flexion angle of 110 degrees.

Pincivero et al. [17] reports a higher slope for men than for women. In our experiments we found out that the stronger the subjects the higher the slopes of the ascending and descending limb.

To sum it up gender, age and hip flexion angle showed influences for both force directions. Knowing the general curve shape and just translating functions using the maximum value turns out to be inaccurate as the slope depends on the intercept.

The resulting joint torque- joint angle functions can now be implemented in digital human models as an intermediate step for posture and strength prediction. Thus workplaces and products can be evaluated in terms of relative joint loads [28] and resulting postures.

Combinations with extensive measurement campaigns will finally lead to absolute strength values expressed in percentiles [28].

Acknowledgments. The research leading to these results has received funding from the European Community's Seventh Framework Programme (FP7/2007-2013) under grant agreement no 218525. The authors gratefully acknowledge the support of the TUM Graduate School at Technische Universität München, Germany.

References

1. Daams, B.: Human force exertion in user-product interaction. backgrounds for design. Delft: Fac. of Industrial Design Engineering, Delft Univ. of Technology (Series in physical ergonomics, 2) (1994)
2. Chaffin, D.B.: Prediction of Population Strength. In: Proceedings of the SAE DHMC (Digital Human Modeling Conference), H. SAE 981307 (1998)
3. Schwarz, W.: 3D-Video-Belastungsanalyse. Ein neuer Ansatz zur Kraft- und Haltungsanalyse. Als Ms. gedr. Düsseldorf: VDI-Verl (Fortschritt-Berichte VDIReihe 17, Biotechnik/Medizintechnik, 166) (1997)
4. Winter, D.A.: Biomechanics and motor control of human movement, 3rd edn. Wiley, Hoboken (2005)
5. Seitz, T., Recluta, D., Zimmermann, D., Wirsching, H.-J.: FOCOPP - An approach for a human posture prediction model using internal/external forces and discomfort. In: Proceedings of the SAE DHMC (Digital Human Modeling Conference), H. SAE 2005-01-2694 (2005)
6. Campney, H.K., Wehr, R.W.: Significance of strength variation through a range of joint motion. Phys. Ther. (45), 773–779 (1965)
7. Knapik, J.J., Wright, J.E., Mawdsley, R.H., Braun, J.: Isometric, Isotonic, and Isokinetic Torque Variations in 4 Muscle Groups Through a Range of Joint Motion. Physical Therapy 63(6), 938–947 (1983)
8. Yoon, S.T., Park, D.S., Kang, S.W., Chun, S.-I., Shin, J.S.: Isometric and Isokinetic Torque Curves at the Knee Joint. Yonsei Medical Journal 32(1), 33–43 (1991)
9. Anderson, D.E., Madigan, M.L., Nussbaum, M.A.: Maximum voluntary joint torque as a function of joint angle and angular velocity: Model development and application to the lower limb. Journal of Biomechanics 40(14), 3105–3113 (2007)
10. Samuel, D., Rowe, P.J.: Effect of Ageing on Isometric Strength through Joint Range at Knee and Hip Joints in Three Age Groups of Older Adults. Gerontology 55(6), 621–629 (2009)
11. Houtz, S., Lebow, M., Beyer, F.: Effect of posture on strength of the knee flexor and extensor muscles. Journal of Applied Physiology (11), 475–480 (1957)
12. Williams, M., Stutzmann, L.: Strength variation through the range of motion. Phys. Ther. (39), 145–152 (1959)
13. Mohamed, F., Perry, J., Hislop, H.: Relationship between wire EMG activity, muscle length, and torque of the hamstrings. Clinical Biomechanics 17(8), 569–579 (2002)
14. Kulig, K., Andrews, J.G., Hay, J.G.: Human strength curves. In: Terjung, R.L. (ed.) Exercise and Sport Science Reviews, vol. (12), pp. 417–466. The Collamore Press, Lexington (1984)
15. Campney, H.K., Wehr, R.W.: An interpretation of the strength differences associated with varying angles of pull. Res. Q (36), 403–412 (1965)
16. Lindahl, O., Movin, A., Rindqvist, I.: Knee extension measurement of the isometric force in different positions of the knee joint. Acta Orthop. Scand. (40), 79–85 (1969)
17. Pincivero, D.M., Salfetnikov, Y., Campy, R.M., Coelho, A.J.: Angle- and gender-specific quadriceps femoris muscle recruitment and knee extensor torque. Journal of Biomechanics, 1689–1697 (2007)
18. Becker, R., Awiszus, F.: Physiological alterations of maximal voluntary quadriceps activation by changes of knee joint angle. Muscle & Nerve 24(5), 667–672 (2001)
19. Haffajee, D., Moritz, M., Svantensson, G.: Isometric knee extension strength as a function of joint angle, muscle length and motor unit activiy. Acta Orthop. Scand. (43), 138–147 (1972)

20. Herzog, W., Hasler, E., Abrahamse, S.K.: A comparison of knee extensor strength curves obtained theoretically and experimentally. Medicine and Science in Sports and Exercise 23(1), 108–114 (1991)
21. Hurley, B.F.: Age, Gender, and Muscular Strength. Journals of Gerontology Series A-Biological Sciences and Medical Sciences 50, 41–44 (1995)
22. Era, P., Lyyra, A.L., Viitasalo, J.T., Heikkinen, E.: Determinants of isometric muscle strength in men of different ages. European Journal of Applied Physiology and Occupational Physiology 64(1), 84–91 (1992)
23. Herzog, W.: Determinants of muscle strength. Muscle Strength, 45–82 (2004)
24. Goodpaster, B.H., Park, S.W., Harris, T.B., Kritchevsky, S.B., Nevitt, M., Schwartz, A.V., et al.: The loss of skeletal muscle strength, mass, and quality in older adults: The health, aging and body composition study. Journals of Gerontology Series A-Biologicl Sciences and Medical Sciences 61(10), 1059–1064 (2006)
25. Bemben, M.G., Massey, B.H., Bemben, D.A., Misner, J.E., Boileau, R.A.: Isometric Muscle Force Production as a function of age in healthy 20 to 74-yr-old men. Medicine and Science in Sports and Exercise 23(11), 1302–1310 (1991)
26. Frontera, W.R., Hughes, V.A., Lutz, K.J., Evans, W.J.: A cross-sectional study of muscle strength and mass in 45-year-old to 78-yr-old men and women. Journal of Applied Physiology 71(2), 644–650 (1991)
27. Izquierdo, M., Ibañez, J., Gorostiaga, E., Garrues, M., Zúñiga, A., Antón, A., et al.: Maximal strength and power characteristics in isometric and dynamic actions of the upper and lower extremities in middle-aged and older men. Acta Physiologica (167), 57–68 (1999)
28. Engstler, F., Bubb, H.: Generation of Percentile Values for Human Joint Torque Characteristics. In: Duffy, V.G. (ed.) ICDHM 2009. LNCS, vol. 5620, pp. 95–104. Springer, Heidelberg (2009)
29. Kumar, S.: Muscle strength. CRC Press, Boca Raton (2004)
30. Mital, A., Kumar, S.: Human muscle strength definitions, measurement, and usage: Part I - Guidelines for the practitioner. International Journal of Industrial Ergonomics 22(1-2), 101–121 (1998)
31. Brown, L.E., Weir, J.P.: ASEP Procedures recommendation 1: Accurate Assessment of muscular strength and power. Journal of Exercise Physiology (online) 4(3) (2001)
32. Chaffin, D.B., Andersson, G., Martin, B.J.: Occupational biomechanics, 4th edn. Wiley-Interscience, Hoboken (2006)