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Precision, comfort and mechanical performance of the Quadriso-tester, a quadriceps force measuring device

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Abstract—*The mechanical performance, repeatability and comfort of the Quadriso-tester, which assesses isometric knee extensor muscle strength, were examined. Twenty healthy subjects and 20 patients treated for unilateral anterior* ligamenta cruciata *insufficiency were tested. Intra-rater repeatability was determined by the testing and retesting of subjects and calculation of the intra-class correlation coefficient and the mean difference between test and retest values. The comfort level was determined a questionnaire. Measuring time was recorded, and the relationship between knee angle and extension moment was plotted. Strength and stiffness were determined using the finite element method. Intra-rater repeatability was high; the intra-class correlation coefficient of the right and left leg was 0.90 and 0.91, respectively; the coefficient of variation was 6.4 and 6.0%, respectively. The median comfort score of the healthy subjects was 7, and that of the patients was 9. Measuring time remained within 30 min. Misalignment of the knee and sidebar axis disturbed the relationship between knee angle and extension moment. Strength and stiffness were higher than required. In conclusion, the Quadriso-tester is a comfortable and fast device to determine quadriceps force with a high repeatability. The knee and sidebar axis should be well aligned.*

Keywords—*Exercise, Equipment, Isometric, Muscle strength*

Med. Biol. Eng. Comput., 2003, **41**, 283–289

1 Introduction

IN ALL activities that are performed while standing, walking or running, knee extensor muscle activity is essential. Knee extensor weakness has a major influence on daily activities such as chair rising, standing and walking and can be caused by muscle disease, trauma or age (BROOKS and FAULKNER 1994; LARSSON *et al.*, 1979). GURALNIK *et al.* (1994) found that poor performance of the elderly in gait speed, chair rising and tandem stands predicted increased future disability, nursing home admission and mortality in community-dwelling older adults. Possible relationships between loss of muscle strength and disabilities are shown in the conceptual model of the disablement process defined by VERBRUGGE and JETTE (1994).

To improve muscle strength, isokinetic, isometric and isotonic exercises are used (FRONTERA *et al.*, 1988; GRIMBY *et al.*, 1992; MIKESKY *et al.*, 1994; NICHOLS *et al.*, 1993; SKELTON *et al.*, 1995; SKELTON and MCLAUGHLIN, 1996; WESTHOFF *et al.*, 2000).

Measuring knee extensor muscle strength in a standardised manner is essential for the diagnosis of muscle condition and the evaluation of training programmes associated with knee extensor muscle strength (WESTHOFF *et al.*, 2000; LEMMINK, 1996). Several measuring devices and methods for assessing knee extensor muscle strength exist, ranging from large, multi-functional isokinetic dynamometers, such as the Cybex II (JENSON *et al.*, 1971), to hand-held force transducers (AGRE *et al.*, 1987; HARLAAR *et al.*, 1996). None of these devices is suitable for a fast, simple and cheap assessment of knee extensor muscle strength, with high repeatability. Isokinetic dynamometers are expensive, bulky and relatively immobile. Operating and data handling are time-consuming. Hand-held dynamometers must be kept in position by the therapist, which is difficult for moderate to high extensor forces owing to the limitation of the maximum arm strength of the therapist (AGRE *et al.*, 1987; ANDREWS *et al.*, 1996; HARLAAR *et al.*, 1996), making it unreliable for the lower-extremity muscle groups (AGRE *et al.*, 1987).

An improvement is the integration of a hand-held dynamometer into an anchoring station (NADLER *et al.*, 2000). Another solution is offered by the Quadriso-tester, a new measuring device developed to measure the knee extensor moment during an isometric contraction. The mechanical performance, repeatability and comfort of the Quadriso-tester are not known and are therefore the subject of the study discussed in this paper.

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2 Method

2.1 *Device*

The Quadriso-tester consists of a bench and measuring equipment (Fig. 1). Sitting down is possible if the measuring equipment is removed. The height of the bench is 650 mm, and so most people's legs will not touch the floor. An armset is mounted on the seat for support. Holding the armset during the exercise minimises lifting of the body. The back of the knee must be in contact with the front of the seat. The measuring set-up can be placed in front of the left or right lower leg. The angle between upper and lower leg can be varied between 90° (sitting posture) and 180° (maximum extension) in steps of 15°. A force transducer* is positioned 15 cm above the malleoli of the ankle by being slid along the two sidebars. The force transducer is covered by a pad to minimise pressure on the tibia. Forces up to 5000 N can be measured, with a maximum error of 0.3% according to the manufacturer. The distance between the centre of the force transducer and the rotation axis of the side bar is indicated on the side bar. This distance multiplied by the measured force determines the moment of the knee extensor muscles. The rotation axis of the side bar is assumed to correlate in general with the rotation axis of the knee.

2.2 *Mechanical analysis*

The mechanically most critical part of the design, the sidebar, was analysed for strength and stiffness using the finite element method program Ansys†. The lower end of the sidebar was loaded with a force of 640 N, resulting in a bending moment of 300 Nm, the maximum expected knee extensor moment (ENOKA, 1994). The sidebar, made of an aluminium alloy (AlMgSi), was characterised by a Young's modulus of 7000 MPa and a safety stress of 250 MPa (BAAIJ *et al.*, 2000). Internal Von Mises stresses and the deformation of the lower end of the sidebar were calculated.

2.3 *Subjects*

Twenty healthy subjects (18 males and two females), who did not have a history of significant injury to the knee, and 20 patients (12 male and eight female) participated in this study. The mean age of the healthy subjects was 28.1 years, ranging from 22 to 44 years, with a standard deviation (SD) of 6.5 years; mean body length was 182.6, range = 167–196, and SD = 8.1 cm; mean weight was 76.1, range = 51–92, and SD = 10.1 kg. The mean age of the patients was 28.2 years, ranging from 16 to 43 years and with SD of 8.0 years; mean body length was 180.8, range = 160–199 and SD = 8.9 cm; mean weight was 75.7, range = 60–100, and SD = 11.0 kg; both groups were therefore comparable. All patients suffered from unilateral anterior *ligamenta cruciata* insufficiency ($n = 7$) or underwent a unilateral anterior *ligamenta cruciata* reconstruction ($n = 13$). The interval from injury or reconstruction to test was 1 year at most. They all participated in a rehabilitation programme.

Informed consent was obtained from all subjects.

2.4 *Procedure*

All subjects were asked to take their place on the seat, with the back of the knee positioned just against the seat. The force transducer was placed 15 cm above the malleoli of the ankle. The distance from the centre of the force transducer to the knee axis was read from the sidebar and registered. Subjects were asked gradually to build up a maximum extension force in 3 s (when this was realised in a longer period of time, the measured value was accepted); subjects were not encouraged. When a subject applied an explosive force (realised within 0.5 s instead of 3 s), the measured value was excluded. The maximum extension moment exerted was visible for the subjects on an LCD screen during the test. One therapist performed the measurements with the healthy subjects; another therapist performed the measurements with the patients.

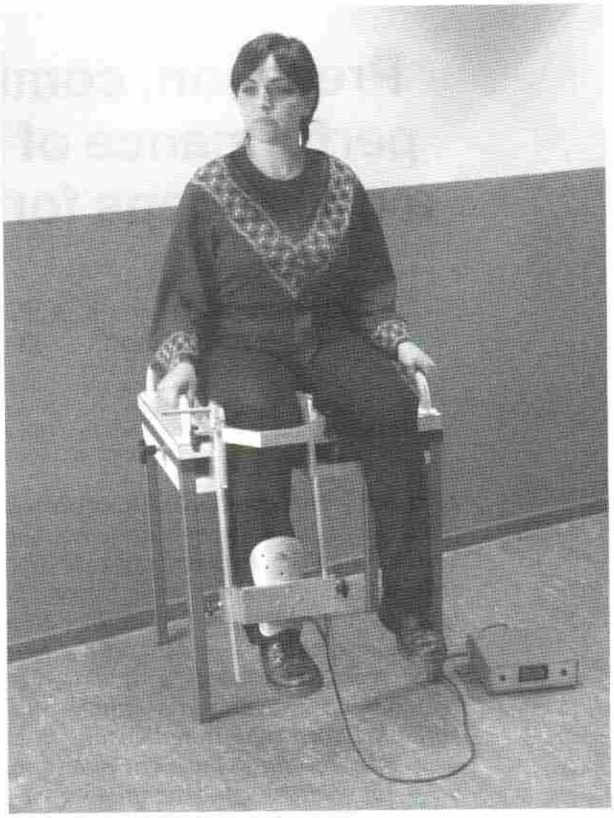

Fig. 1 *Prototype of Quadriso-tester*

First, the left leg was measured, and then, after 30 s, the right leg was measured. For the patient group, first the non-affected and then the affected leg were measured. This was performed three times, and so subjects performed three trials for each leg, with a 1 min rest for the leg between each trial. The highest score per leg was registered. During the measurements, subjects were asked to hold their back in a straight position and to place their hands on the bar along the seat. Switching between the left and right legs involved removal of the measuring set-up and its being replaced under the bench. The healthy subjects performed this procedure for six different knee angles: 90°, 105°, 120°, 135°, 150° and 165°; the patients performed the procedure for only three different knee angles: 90°, 120° and 150°, to prevent overloading of the affected knee. The total muscle load was such that muscle fatigue was not expected (STULEN and DE LUCA, 1982). The knee angle was adjusted by two handles being removed, the sidebars being rotated and the handles being replaced.

To determine test-retest repeatability, a second series of measurements were performed, with the healthy subjects and the same therapist, one day later, at the same time of the day as the first series of measurements. Knee angle was set at 90°, 105°, 135° and 150°; not all angles were retested, to keep the subjects motivated.

To determine the comfort of the testing device, subjects were asked to give their opinion on four topics: comfort of the seat,

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*LC-500kN, Kyowa, 3-8 Toranomon 2-chome, Minato-ku, Tokio, Japan

†Ansys Inc., Southpointe, 275 Technology Drive, Canonsburg PA 15317, USA

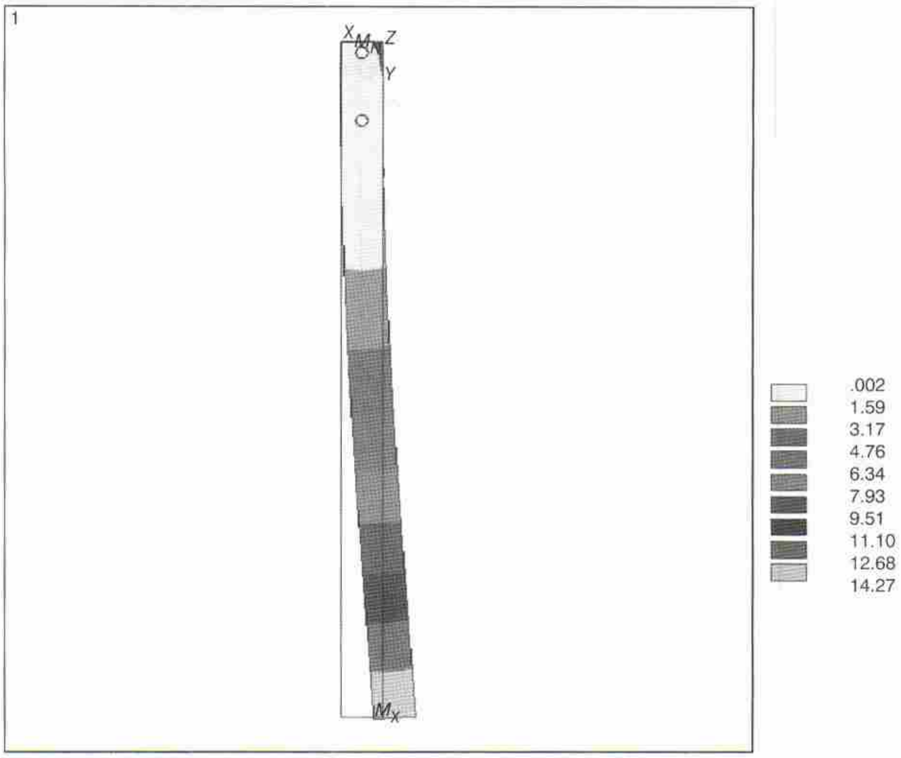

Fig. 2 *Horizontal deformation of sidebar, as calculated by Ansys. Deformation is given in blocks. Upper and lower limits of each block are given in mm.*

pain on the tibia, pain at the back of the knee and muscle pain. A nine-point scale (1–9) was used, with 1 = uncomfortable or much pain, and 9 = comfortable or no pain. The patients were asked two additional questions: whether they experienced pain somewhere else and whether they were afraid to produce maximum force. Again, a nine-point scale was used, ranging from very much to not at all. Finally, the time needed to perform the first series of measurements was determined.

2.5 *Data analysis*

The maximum value of the internal Von Mises stresses, as calculated by the finite element method program, and its location were determined. It was checked whether this value exceeds the safety value (250 MPa). Also, the maximum deformation of the sidebar was determined. The maximum deformation should remain below 2° to keep the difference between the adjusted

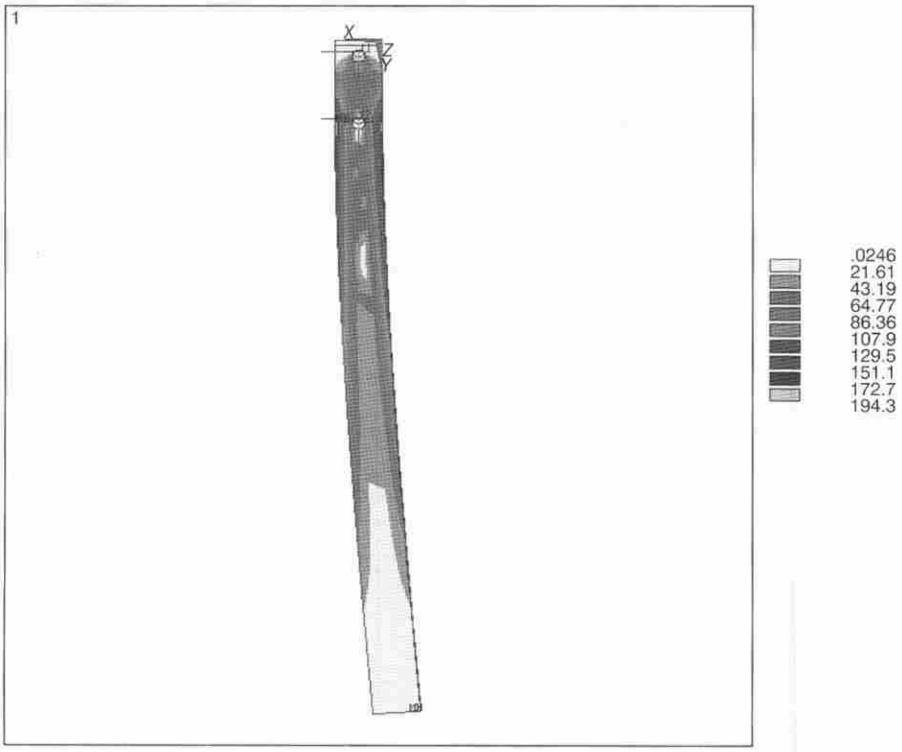

Fig. 3 *Internal Von Mises stresses in sidebar, as calculated by Ansys. Stresses are given in blocks. Upper and lower limits of each block are given in MPa*

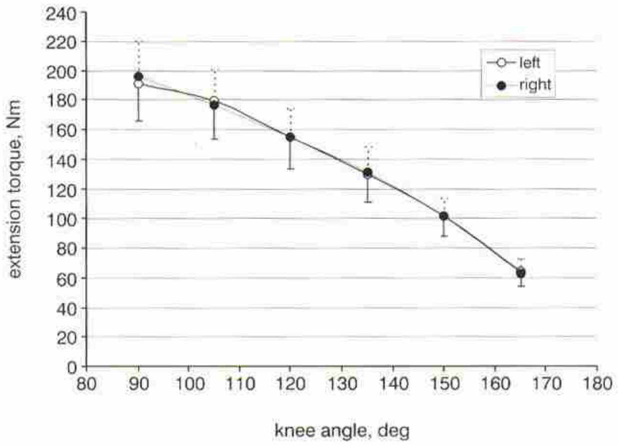

Fig. 4 *Relationship between mean extension moment and knee angle for each leg of healthy subjects and for first series of measurements. (–○–) Left leg; (–●–) right leg. To distinguish left and right leg error bars, only half error bar is shown. Data are based on measurements of 18 healthy subjects*

and real angles between the upper and lower legs acceptable and, consequently, to limit the error in the relationship between knee angle and extension moment.

Measured extension moments were corrected for gravity forces: The mass G (kg) of the lower leg was determined by (WINTER, 1979)

$$G = \text{body weight (kg)} \times 0.061$$

The distance from the knee to the location of the centre of gravity L(m) was determined by (WINTER, 1979)

$$L = L_l(\text{m}) \times 0.606$$

with L_l = length of the lower leg = 0.277 × body length (MOLENBROEK and DIRKEN).

The extra extension moment M_e(Nm), performed by the quadriceps to raise the lower leg, is

$$M_e = G \times 9.81 \times L \times \cos(180^\circ - a)$$

where a = knee angle.

Therefore the total extension moment M_e(Nm) of the quadriceps is

$$M_m = M_e + a.F$$

where a = the distance between the centre of the force transducer and the rotation axis of the sidebar, and F = the force measured by the force transducer.

2.6 *Statistical analysis*

For each leg and each knee angle, the intra-class correlation coefficient (ICC) between the values of the first and second series of measurements was calculated for all healthy subjects. ICC values above 0.80 are indicative of good repeatability (BAUMGARTNER and JACKSON, 1991). Another indicator of repeatability was used: for each angle, the 95% confidence interval of the differences between the values of the first and second series of measurements was considered. When 0 was in that interval, the repeatability was supported. When 0 was not in that interval, the difference between the values of the first and second series of measurements was apparently considerable.

In addition, for each leg and each angle, the coefficient of variation (CV) was calculated for all healthy subjects.

The comfort score was analysed by determining the median, maximum and minimum values of both the healthy subjects and the patient group.

Table 1 Knee extensor moment (in Nm) of right leg of healthy subjects for six different knee angles (in degrees). Mean and SD of first and second series of measurements are given. CV (in %), ICC, and 95% confidence interval of difference between first and second series over all subjects are given per knee angle. When 0 is in that interval, values are in italic. Finally, mean CV and ICC over 4 angles are given

	Mean, Nm		SD, Nm				
Knee angle, degree	series 1	series 2	series 1	series 2	CV, %	ICC	95% interval, Nm
90	196.2	181.3	48.7	46.4	6.6	0.92	1.4–10.3
105	176.7	164.1	47.7	45.4	8.0	0.89	*−0.2–9.1*
120	155.0		38.1				
135	131.5	120.5	32.4	27.4	7.1	0.89	*−3.4–6.3*
150	101.8	101.3	22.3	20.6	4.1	0.91	*−0.2–3.5*
165	62.8		18.7				
Mean over 4 angles					6.4	0.90	

Table 2 Knee extensor moment (in Nm) of left leg of healthy subjects for six different knee angles. See Table 1 for details

	Mean, Nm		SD, Nm				
Knee angle, degree	series 1	series 2	series 1	series 2	CV, %	ICC	95% interval, Nm
90	191.0	177.9	50.3	46.9	5.6	0.94	1.4–8.8
105	179.2	173.2	51.7	50.7	7.6	0.89	*−3.3–7.4*
120	154.0		42.9				
135	128.5	118.3	36.5	25.5	6.8	0.86	*−6.9–4.8*
150	99.7	104.4	26.5	33.4	4.0	0.96	*−2.6–4.0*
165	62.2		19.2				
Mean over 4 angles					6.0	0.91	

Table 3 Comfort score of Quadriso-tester given by 18 healthy subjects and 20 patients on nine-point scale (1–9, with 1 = low comfort and 9 = high comfort). Median value, maximum (max) and minimum (min) score are listed

	Healthy subjects			Patients		
Topic	median	max	min	median	max	min
Sitting comfort	6.5	9	3	5.5	8	4
Pain on tibia	7	9	2	9	9	3
Pain at back of knee	7.5	9	6	9	9	5
Muscle pain	7.5	8	3	9	9	3
Pain elsewhere				8	9	3
Afraid to produce maximum power				9	9	7
All topics	7			9		

3 Results

3.1 *Mechanical performance*

The deformation of the lower end of the sidebar appeared to be 14 mm (Fig. 2), resulting in an angle of 1.8°. The maximum internal stress appeared to be 194 MPa (Fig. 3), located at the level of the rotating pin.

3.2 *Healthy subjects*

Two healthy subjects were excluded from the study, because they repeatedly applied an explosive force. Table 1 summarises the results of the measurements of the right leg, and Table 2 gives the results for the left leg. The relationship between mean extension moment and knee angle is shown in Fig 4. Mean ICC for the right leg was 0.90, with a range of 0.89–0.92. When the 95% confidence interval of the differences was considered, 0 lay in the interval for three of the four angles, thus supporting the repeatability. Mean ICC for the left leg was 0.91, with a range of 0.86–0.96.

When the 95% confidence interval of the differences was considered, 0 lay in the interval for three of the four angles, thus supporting the repeatability.

Mean CV for the right leg was 6.4%, with a range of 4.1–8.0%. Mean CV for the left leg was 6.0%, with a range of 4.0–7.6%.

The comfort scores of the healthy subjects are summarised in Table 3. Subjects showed a diverging opinion, ranging from 2 to 9. The median score was 7.

For each subject, the first series of measurements could be performed within 30 min.

3.3 *Patients*

Table 4 summarises the results of the measurements. On the basis of knee extension moment, the patients could be divided into two groups, the first showing a higher extension moment at 120° than at 90° (Fig. 5), and the second showing a higher extension moment at 120° than at 90° (Fig. 6). The comfort scores of the Quadriso-tester are summarised in Table 3. Subjects again showed a diverging opinion, ranging from 3 to 9. The median score was 9.

4 Discussion

To determine whether the Quadriso-tester is a fast and simple measuring device with a high repeatability for the assessment of knee extensor muscle strength, a study has been performed for 20 healthy subjects and 20 patients suffering from *ligamenta cruciata* insufficiency. Performing measurements with the Quadriso-tester appeared to be simple. Preparation of the Quadriso-tester is limited to switching the power supply on. Performing knee angle adjustment and left–right switching is simple. The complete series of measurements (6 different angles × 2 legs ×3 measurements per leg and angle = 36 measurements) could be obtained within 30 min. The measurement time was largely determined by the required period of rest (30 s) between the measurement with the left leg and the subsequent measurement with the right leg. Switching from one leg to the other could well be performed within this period.

The comfort of the Quadriso-tester was experienced quite differently by the healthy subjects. The median score (of all subjects and questions) was 7, and the score varied between 5.5 and 8 per subject.

Pain at the back of the knee and muscle pain scored best in general (median score was 7.5); sitting comfort scored worst (median score was 6.5). The general score of 7 is sufficient, but indicates that comfort should be improved. The patient group was even more satisfied: the median score (of all subjects and questions) was 9, varying per subject between 6.5 and 9. Four items (pain on tibia, pain at the back of the knee, muscle pain, afraid to produce maximum power) scored best (median score was 9), and again sitting comfort scored worst (median score was 5.5). Although patients suffered from knee ligament insufficiency, they all said that they were not afraid to produce maximum force (scores were 7 or higher). Measured knee moments at 120° and 150° confirm this statement, because the knee moments were comparable with those of the healthy subjects. Measured knee moments at 90° were somewhat lower than those of the healthy subjects.

During the measurements, extensor moments up to 306 Nm were realised. For such a load, the construction appeared to be strong and stiff enough. When such extension moments are applied, elastic deformation of the construction leads to a change in knee angle of 1.8° at most, which is acceptable. Compared

Table 4 Knee extensor moment (in Nm) of leg of 20 patients for three different knee angles. Mean and SD of measurements are given

	Non-affected leg		Affected leg	
Knee angle, degree	mean, Nm	SD, Nm	mean, Nm	SD, Nm
90	162.2	56.8	119.0	48.5
120	165.1	59.6	127.4	48.9
150	113.2	33.0	89.0	27.5

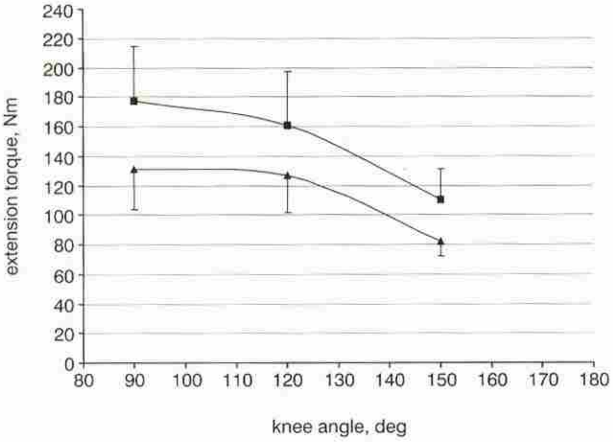

Fig. 5 *Relationship between mean extension moment and knee angle for each leg of first patient group. (-■-) Normal; (-▲-) affected. To distinguish left and right leg error bars, only half error bar is shown. Data are based on measurements of 9 patients*

with measurements obtained using hand-held dynamometers, the knee angle varied less during measurements with the Quadriso-tester. Internal stresses (194 MPa) remained below the safety stress of 250 MPa.

The relationship between applied moments and knee angles of the second patient group, as depicted in Fig. 6, is in accordance with the results of other studies (RALSTON and TODD, 1981; ENOKA, 1994). The relationship between applied moments and knee angles of the first patient group, depicted in Fig. 5, is comparable with that of the healthy subjects, depicted in Fig. 4. Both groups show a high extension moment at 90°, leading to a constantly declining curve. In this regard, these results differed from other studies (RALSTON and TODD, 1981; ENOKA, 1994). The division in patients based on 'suffering from *ligamenta cruciata* insufficiency' or 'having a *ligamenta cruciata* reconstruction' did not correlate with the division in patients concerning the relationship between applied moments and knee angles according to Fig. 5 or Fig. 6. It is more likely that interindividual differences cause the different relationships between applied moments and knee angles, as these differences can be substantial (ENOKA, 1994).

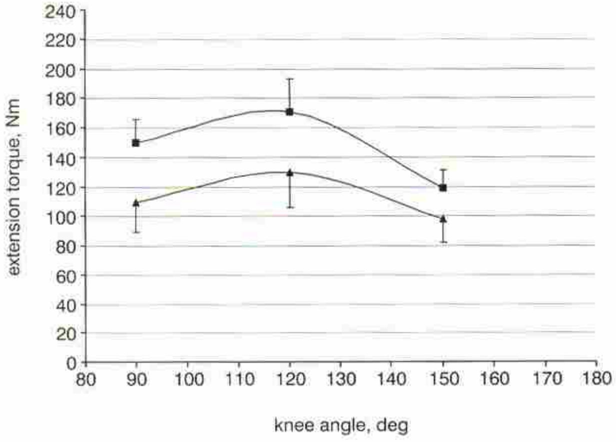

Fig. 6 *Relationship between mean extension moment and knee angle for each leg of second patient group. (-■-) Normal; (-▲-) affected. To distinguish left and right leg error bars, only half error bar is shown. Data are based on measurements of 11 patients*

For the healthy subjects, the force of the left knee extensor muscles was slightly less than the force of the right ones, except at a knee angle of 105°. Patient results show that, indeed, the affected leg is less powerful than the healthy one. For all knee angles, a mean decrease of about 24% was measured.

The mean values per angle and per leg of the second series were, in general, lower than those of the first series. However, the difference was only significant for knee angles of 90°. The same phenomenon was found by LEMMINK (1996).

Mean ICC for the right leg is 0.90, and that for the left leg is 0.91. These findings are in accordance with the results of a former prototype of the Quadriso-tester: LEMMINK *et al.* (2001) found a good intra-rater repeatability (female subjects' $r=0.83$; male subjects' $r=0.97$) and inter-rater repeatability (female subjects' $r=0.93$; male subjects' $r=0.86$). When compared with a hand-held dynamometer that showed an ICC ranging from 0.41 to 0.81 (AGRE *et al.*, 1987), the Quadriso-tester results are superior. The Quadriso-tester ICC is comparable with that of a hand-held dynamometer build into an anchoring station, which also showed a high ICC score of 0.94 (NADLER *et al.*, 2000).

The mean CVs of the right and left legs (6.4 and 6.0%, respectively) again indicate high intra-rater repeatability. AGRE *et al.* (1987) found a mean CV for the hand-held dynamometer of 11.3%, NADLER *et al.* (2000) found one of 8.1% for the hand-held dynamometer built into an anchoring station.

5 Conclusions

The Quadriso-tester appeared to be a comfortable, mechanically strong and stiff device for measuring leg extension moments and, based on the ICCs and CVs, the repeatability is better than that of hand-held dynamometers, and it so is suitable for use in rehabilitation medicine.

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References

AGRE, J. C., MAGNESS, J. L., HULL, S. Z., *et al.* (1987): 'Strength testing with a portable dynamometer: reliability for upper and lower extremities', *Arch. Phys. Med. Rehabil.*, **68**, pp. 454–458

ANDREWS, W. A., THOMAS, M. W., and BOHANNON, R. W. (1996): 'Normative values for isometric muscle force measurements obtained with hand-held dynamometers', *Phys. Therapy*, **76**, pp. 248–259

BAAIJ, J., BEIJER, J., BEUKERS, A., *et al.* (2000): 'Engineering dossiers, technical materials (in Dutch)' (Ten Hagen Stam, The Hague, 2000)

BAUMGARTNER, T. A., and JACKSON, A. S. (1991): 'Measurement for evaluation in physical education and exercise science' (Wm C. Brown Publ, Dubuque, 1991)

BROOKS, S. V., and FAULKNER, J. A. (1994): 'Skeletal muscle weakness in old age: underlying mechanisms', *Med. Sci. Sports Exerc.*, **26**, pp. 432–439

ENOKA, R. M. (1994): 'Neuromechanical basis of kinesioloy', 2nd edn (Human Kinetics, Champaign, IL, 1994)

FRONTERA, W. R., MEREDITH, C. N., O'REILLY, K. P., *et al.* (1988): 'Strength conditioning in older men: skeletal muscle hypertrophy and improved function', *J. Appl. Physiol.*, **64**, pp. 1038–1044

GRIMBY, G., ANIANSSON, A., HEDBERG, M., *et al.* (1992): Training can improve muscle strength and endurance in 78-to 84-yr-old men. *J. Appl. Physiol.*, **73**, pp. 2517–2523

GURALNIK, J. M., SIMONSICK, E. M., FERRUCCI, L., *et al.* (1994): A short physical performance battery assessing lower extremity function: association with self-reported disability and prediction of mortality and nursing home admission. *J. Gerontology.*, **49**, pp. 85–94

Harlaar, J., Roebroeck, M. E., and Lankhorst, G. J. (1996): Computer-assisted hand-held dynamometer: low cost instrument for muscle function assessment in rehabilitation medicine. *Med. Biol. Eng. Comput.*, **34**, pp. 329–335

Jenson, R. H., Smidt, G. L., and Johnston, R. C. (1971): A technique for obtaining measurements of force generated by hip muscles. *Arch. Phys. Med. Rehabil.*, **52**, pp. 207–215

Larsson, L., Grimby, G., and Karlsson, J. (1979): 'Muscle strength and speed of movement in relation to age and muscle morphology'. *J. Appl. Physiol.*, **46**, pp. 451–456

Lemmink, K. (1996): 'De Groninger Fitheidstest voor ouderen: ontwikkeling van een meetinstrument.' dissertation, Univ. of Groningen, Groningen, The Netherlands

Lemmink, K. A. P. M., Kemper, H. C. G., De Greef, M. H. G., *et al.* (2001): 'The reliability of the Groningen fitness test for the elderly', *J. Aging Phys. Activity*, **9**, pp. 194–212

Mikesky, A. E., Topp, R., Wigglesworth, J. K., *et al.* (1994): 'Efficacy of a home-based training program for older adults using elastic tubing', *Eur. J. Appl. Physiol.*, **69**, pp. 316–320

Molenbroek, J. F. M., and Dirken, J. M. (1986): *Dined table with Dutch antropometric data.* Available from: http://www.io.tudelft.nl/research/ergonomics/frame_research.htm

Nadler, S. F., DePrince, M. L., Hauesien, N., *et al.* (2000): 'Portable dynamometer anchoring station for measuring strength of the hip extensors and abductors', *Arch. Phys. Med. Rehabil.*, **81**, pp. 1072–1076

Nichols, J. F., Omizo, D. K., Peterson, K. K., and Nelson, N. P. (1993): 'Efficacy of heavy resistance training for active women over sixty: muscular strength, body composition, and program adherence', *J. Am. Geriatrics Soc.*, **41**, pp. 205–210

Ralston, H. J., and Todd, F. (1981): 'Human walking' (Williams & Wilkens, Baltimore, 1981)

Roebroeck, M. E., Harlaar, J., and Lankhorst, G. J. (1998): 'Reliability assessment of isometric knee extension measurement with a computer-assisted hand-held dynamometer', *Arch. Phys. Med. Rehabil.*, **79**, pp. 442–448

Skelton, D. A., Young, A., Greig, C. A., and Malbut, K. E. (1995): 'Effects of resistance training on strength, power, and selected functional abilities of women aged 75 and older'. *J. Am. Geriatrics Soc.*, **43**, pp. 1081–1087

Skelton, D. A., and McLaughlin, A. W. (1996): 'Training functional ability in old age', *Physiotherapy*, **82**, pp. 159–167

Stulen, F. B., and De Luca, C. J. (1982): 'Muscle fatigue monitor: a noninvasive device for observing localized muscle fatigue', *IEEE Trans. Biomed. Eng.*, **29**, pp. 760–768

Verbrugge, L. M., and Jette, A. M. (1994): 'The disablement process', *Social Sci. and Med.* **38**, pp. 1–14

Westhoff, M. H., Stemmerik, L., and Boshuizen, H. C. (2000): 'Effects of a low intensity strength-training program on knee-extensor strength and functional ability of frail older people', *J. Aging Physic. Activity*, **8**, pp. 325–342

Winter, D. A. (1979): 'Biomechanics of human movement' (John Wiley, New York, 1979)

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