Forces during squatting and rising from a deep squat

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The joint and muscle forces arising from and generated in the knee during the activity of squatting, and rising from a deep squat have been calculated. The analysis involved the consideration of a two-dimensional model. Data was then collected from each of the subjects performing the activity using: a force platform; a ciné film used in conjunction with the X-rays to describe accurately the configuration of the lower limb; EMG data; anthropometric data. A computer program was developed to analyse the data and compute the forces in the leg. Six subjects were tested and graphs of joint and muscle forces versus knee angle were obtained for each of them. A discussion follows. The results for ascent and descent, and slow and fast activities are compared.

Introduction

Knee forces have been studied in numerous activities but for the most part these studies concentrated on ambulatory activities such as level walking, walking up and down a ramp, as well as climbing and descending stairs (Morrison, 1968). The activity of rising from a chair with and without the aid of arms has also been studied by Ellis *et al* (1979), in which a comparison was made between the forces acting during rising from a normal chair and rising with the aid of a motorized chair. The study of forces during these activities is of importance in the design of internal prostheses, and orthoses as well as the design of seats for the disabled. The study of forces during athletic activities is also of equal importance in that such studies could help in giving advice to avoid injury which is now a frequent occurrence due to the intensity of competitiveness, and the increase in the number of atheletes. Smith (1972) has shown that knee forces of between seventeen and twenty-four times body weight occur in the activity of a drop landing from a one metre height and then falling into a deep squat. The lower value of the force corresponds to what he termed as a 'soft' landing and the higher to a 'hard' landing. Weight lifting has not as yet been studied in so far as knee joint forces are concerned. This paper considers knee forces during squatting and rising from a deep squat, being an activity close to that of weight lifting, since the body configuration is similar for a considerable part of the activity. This study has been undertaken as a final year project in the Department of Mechanical Engineering at Leeds University, and the work carried out at the Rheumatism Research Unit.

Model of the lower leg

In this study, it was justified to consider a two-dimensional model of the lower leg since the lateral forces were small; the component of the internal joint force in the lateral direction was found to be 0.2 times body weight during the walking activity by Morrison (1968), and it would be expected to be much smaller during the activity of rising from a deep squat. Further, the angles between the various major muscles and the long axes of the femur and tibia are small. Finally, the movement of the legs in the lateral direction during this activity is also small. Joint movement occurs mainly in the sagittal plane. This model comprised four segments, the upper leg, the lower leg, and two segments for the foot (see Fig. 1).

The configuration of the thigh, shank and foot are controlled by forces exerted in the muscles surrounding the hip, knee and ankle joints. Only major muscles and muscle groups have been considered in this analysis. These are:

1. The gluteal muscles which are extensors of the hip.

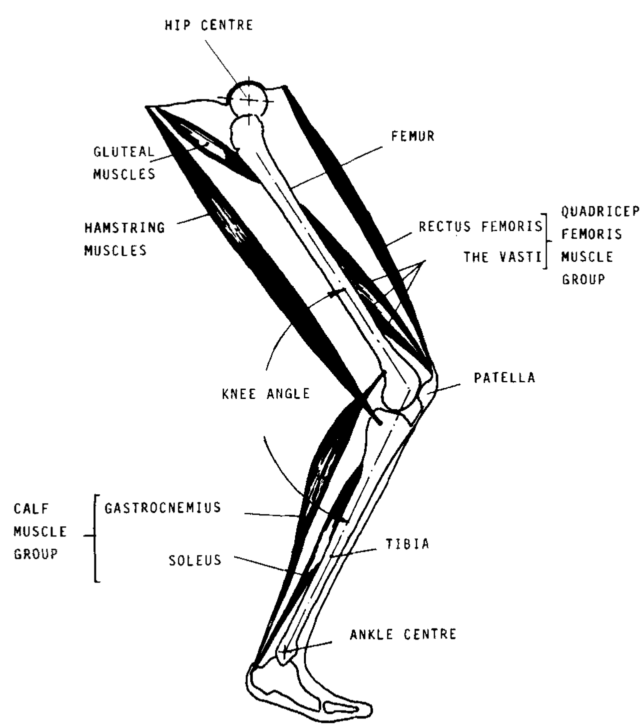

Fig. 1. Model of the lower leg adopted in this study. Four segments were considered. Also shown are the various muscles included

2. The quadriceps femoris; including rectus femoris which is at the same time, an extensor of the knee and a flexor of the hip, and the vasti muscles (including vastus medialis, vastus intermedialis and vastus lateralis) which are extensors of the knee.
3. The hamstrings, which include the long head of the biceps femoris, semimembranosus, and semitendinosus. These muscles tend to flex the knee but also extend the hip.
4. The calf muscles including the two heads of the gastrocnemius (which tend to flex the knee but plantar flex the ankle), and soleus which is a plantar flexor of the ankle.

The assumptions underlying this two-dimensional model have been discussed elsewhere (Seedhom and Terayama, 1976; Ellis *et al*, 1979) but they are briefly stated here with some improvements to the model

(a) For the most part the lines of action of the muscles were considered to be those joining the centroids of the areas of origin and insertion of these muscles to the bone. However, wherever a muscle curved either over bony surfaces or deeper muscles, its line of action was considered to be along the tangent to the curve passing through the centre of the muscle and going through the 'points' of origin or insertion. Such cases were encountered with the quadriceps tendon at the position of deep squat, with the gastrocnemius muscles at the position of full extension, and with the hamstrings at other intermediate positions (Fig. 2).

(b) The muscles within a group were considered to act synchronously. This is based on the well known research carried out in California (1953). However, in the study electromyographic information was obtained in order to ascertain whether this was consistent. In particular, in the case of the quadriceps femoris group, rectus femoris was monitored as well as one of the vasti.

(c) Frictional forces between the articular surfaces of the joint were considered insignificant. This assumption, which led in the past to the patello-femoral compartment being considered as a frictionless pulley with the tensions in the quadriceps tendon and the patellar ligament being equal, had to be modified. The studies by Bishop and Denham (1979), and by Ellis *et al* (1980), have shown that these tensions are not equal since the ratio between them is also a function of the geometry of the patello-femoral joint.

(d) For this model it was assumed that the moment of external and gravitational forces about any joint would be shared equally by the muscles involved in resisting this moment, should the EMG information indicate that more than one muscle group is active at any particular moment. For instance, a moment that tends to flex the hip would be equally shared between the gluteal muscles and the hamstrings, should they both be active. Also a moment that tends to dorsi flex the ankle would be equally shared by soleus and the gastrocnemius muscles. In the case of the quadriceps femoris it was assumed that when the four muscles were active, since the biological cross-sectional area of the individual muscles were almost equal (Alexander and Vernon 1978), the forces exerted by each one of these muscles was one-quarter of the total force acting along the quadriceps tendon.

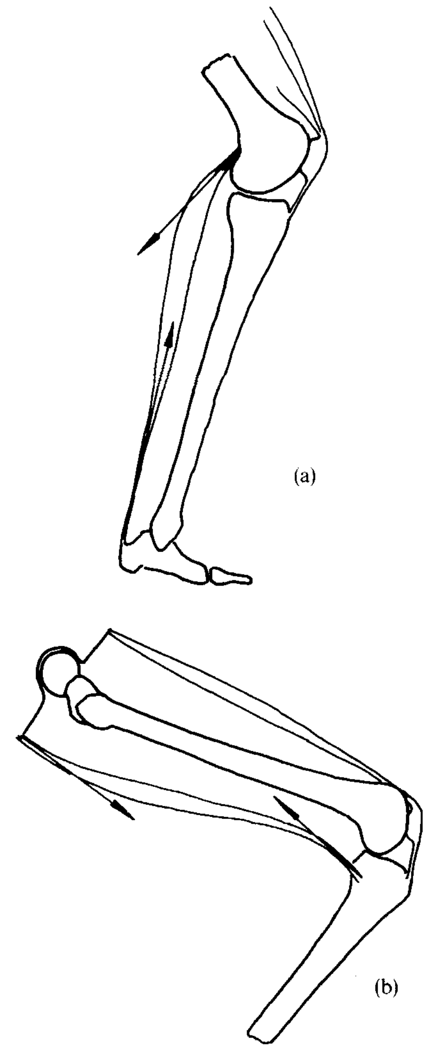

Fig. 2. The line of action of the muscle was not always that joining centroids of areas of origin and insertion of the muscle. In both (a) and (b) are shown examples where muscle forces act along tangents to muscles curving over bony protrusion, deeper muscles or muscles curving due to a skin sling (as in the hamstrings attachment to the tibia)

Nomenclature and analysis of force

Notation

a	moment arm about hip centre
b	moment arm about point of contact of femur and tibia
c	moment arm about ankle centre
Z	vertical component of foot to floor reaction
X	horizontal component of foot to floor reaction
W_1, W_2, W_3	weights of the thigh, shank and foot respectively.
F	force acting in the tibio-femoral compartment vertically
T	force acting in the tibio-femoral compartment horizontally
P	force acting in patello-femoral joint
GAS	force exerted by gastrocnemius muscle group

S	force exerted by soleus muscle
Q'	force acting along patellar ligament
Q	force acting along quadriceps tendon
Q_{CONST}	ratio of forces in quadriceps and patella tendon
V	force exerted by vasti muscle group
R	force exerted by rectus femoris muscle
H	force exerted by hamstring muscle group
GM	force exerted by gluteal muscle group
Ma	moment about ankle centre
Mh	moment about hip centre
Mn	moment about point of contact between femur and tibia

When a moment arm is suffixed by a symbol denoting a force then that moment arm is that of the force. For example, a_{H} is the moment arm of the hamstrings about the hip centre.

Analysis

The analysis of the lower limb that was detailed is based on 'the method of sections'.

If we consider Fig. 3, the moments about the hip centre created by the external force are:

$$Mh = Za_{\text{Z}} + Xa_{\text{X}} - W_1 a_{\text{W1}} - W_2 a_{\text{W2}} - W_3 a_{\text{W3}} \quad (1)$$

This is resisted by three muscles, the rectus femoris, the hamstrings and the gluteal muscles. Hence:

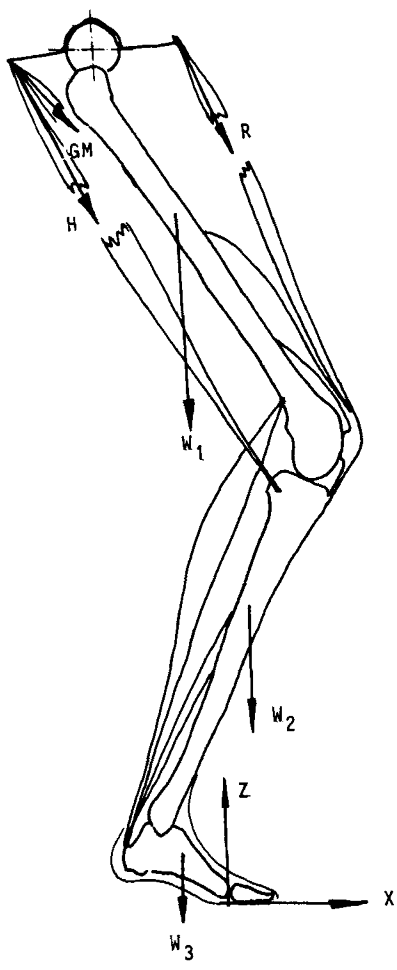

Fig. 3. The moment about the hip's centre of the external and gravitational forces is resisted by the gluteal muscles, the hamstrings and rectus femoris

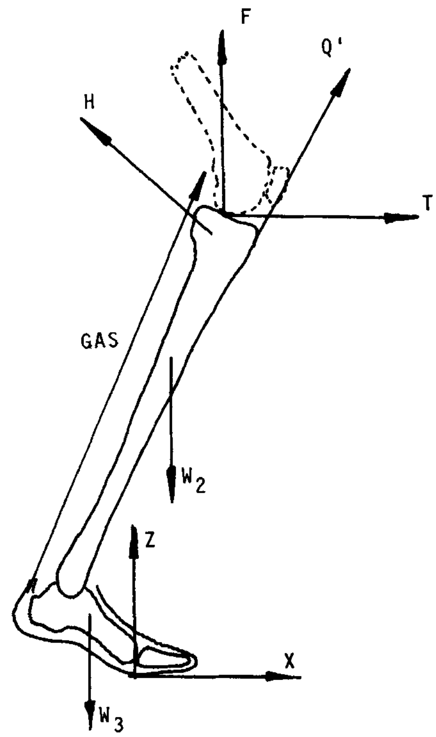

Fig. 4

$$Mh = GMa_{\text{GM}} + Ha_{\text{H}} - Ra_{\text{R}} \quad (2)$$

By subtracting these two equations:

$$Za_{\text{Z}} + Xa_{\text{X}} - W_1 a_{\text{W1}} - W_2 a_{\text{W2}} - W_3 a_{\text{W3}} - GMa_{\text{GM}} - Ha_{\text{H}} + Ra_{\text{R}} = 0 \quad (3)$$

Similarly considering Fig. 4, moments about the point of contact of femur and tibia:

$$Zb_{\text{Z}} + Xb_{\text{X}} + W_2 b_{\text{W2}} + W_3 b_{\text{W3}} - GASb_{\text{GAS}} + Q'b_{\text{Q}} - Hb_{\text{H}} = 0 \quad (4)$$

and for Fig. 5, moments about the ankle centre:

$$Zc_{\text{Z}} + Xc_{\text{X}} - W_3 c_{\text{W3}} - (GAS + S)C_{\text{GAS}} = 0 \quad (5)$$

In the above three equations (3–5) there are six independent unknowns, GAS, S, R, V, H and GM. The forces in the patellar ligament and the quadriceps tendons are unknown but they are not independent. The force in the quadriceps tendon can be calculated by summing the forces in the vasti and the rectus femoris. By considering the force triangle in Fig. 6, and realizing $V = 3R$:

$$Q = R\sqrt{(10 - 6\cos\theta)} \quad (6)$$

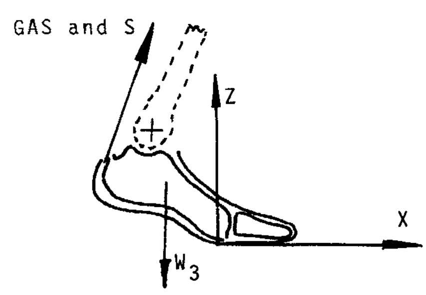

Fig. 5

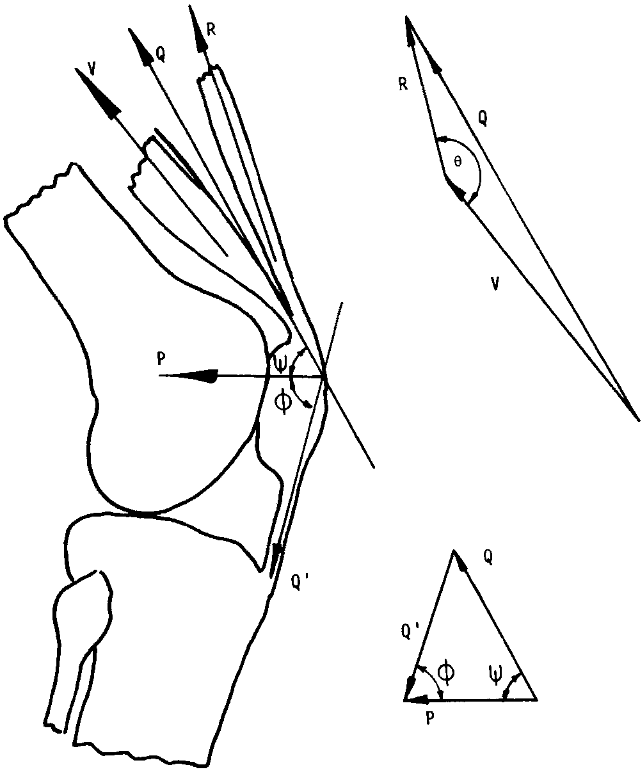

Fig. 6. Forces in the patello-femoral compartment

The relationship between the forces in the patellar ligament and the quadriceps tendon can be found by considering Fig. 6 again. Hence:

$$Q' = Q \sin \psi / \sin \phi \qquad (7)$$

and

$$Q' = R(\sin \psi / \sin \phi)\sqrt{(10 - 6 \cos \theta)} \qquad (8)$$

Although there are only three equations (3–5) and six unknowns, three further equations can be obtained by taking assumption (d) above into consideration. Thus:

$$Ha_{\mathrm{H}} = GMa_{\mathrm{GM}} \qquad (9)$$

$$S = GAS \qquad (10)$$

$$V = 3R \qquad (11)$$

These three equations (9–11) only apply if both muscles represented in any of the equations are active as indicated by the EMG. If one of the muscles is shown to be inactive by the EMG there will only be five unknowns and hence one of the assumptions may be discarded. The EMG data was thus used in a binary form in the computer program, the information being used to select the right equations in order to solve the problem.

The three moment equations (3, 4, 5) can now be expressed in terms of R, H, GAS. The equations are now statically determinate and a value for each force can be computed.

Having a numerical value for each muscle force acting on the knee joint it is possible by resolving in the tibial axis and its perpendicular axis to compute the respective forces along those axes. Similarly the patello-femoral force is simply a matter of resolving forces Q and Q' through the point of contact of the patella and femur.

Experimental techniques and instrumentation

The experimental data required for the analysis were obtained as follows:

1. The external reactions and point of application of the load, Z, X and a_X (this latter being the distance of the point of application of the force measured from the centre of the platform), were measured by a Kistler force platform.
2. The configuration of the lower leg during the activity. This was recorded using a pin registered ciné camera and the speed of the film was 50 frames per second.
3. Anthropometric data; these were:
   (a) The weights of the segments of the lower leg and the positions of their centres of mass were obtained from the published data (Whitsett, 1963).
   (b) The configuration of the bones of the lower leg, their points of contact, and the positions of the origins and insertions of the muscles into the bone, and hence the lines of action of the forces along the muscles, were obtained from X-rays of the lower leg of the subject.
   (c) The centre of the hip joint which was determined experimentally using the Moiré fringe technique described by Lotze (1967) and which has been employed by Amis (1978), for determining the centre of the elbow joint, and by Ellis (1979) in obtaining the centre of the hip joint in his studies of rising from a chair. The technique involves taking a double exposure photograph of the leg, in two different angles of hip flexion, with a grid of parallel lines attached to the upper part of the leg. Using the interference fringes caused by the intersecting lines the hip centre can be found (Fig. 7).
4. Electromyography (EMG) information for which the activity of six muscles was monitored using electrodes which were placed on the skin of the subject. These muscles were rectus femoris, vastus lateralis, gluteus maximus, biceps femoris, the lateral head of gastrocnemius and soleus.

The output of the force platform and the EMG apparatus were simultaneously recorded on a UV oscillograph. In order to synchronize the data recorded on the film, with the force and EMG data, a small electronic circuit was used so that the camera provided a pulse for every frame advanced and this was recorded simultaneously with the platform and EMG outputs.

Analytical procedure: bone model

In this study it was thought useful to consider an almost 'tailor-made' model for each subject. With the help of the X-rays obtained, a cardboard cut-out was made of the femur, tibia and fibula, patella and two segments for the foot. The depths of these bones below the skin were noted and by studying the X-rays and the anatomy of the lower leg, and by examining skeletons it was possible to identify with a degree of accuracy the exact positions of the insertions of the muscles into the bones. Following this procedure, the film taken of the subject was projected to a life-size magnification on the surface of a freescan digitizer and the bone model superimposed on the image making use of different guides and anatomical landmarks. The ankle was the easiest to position since

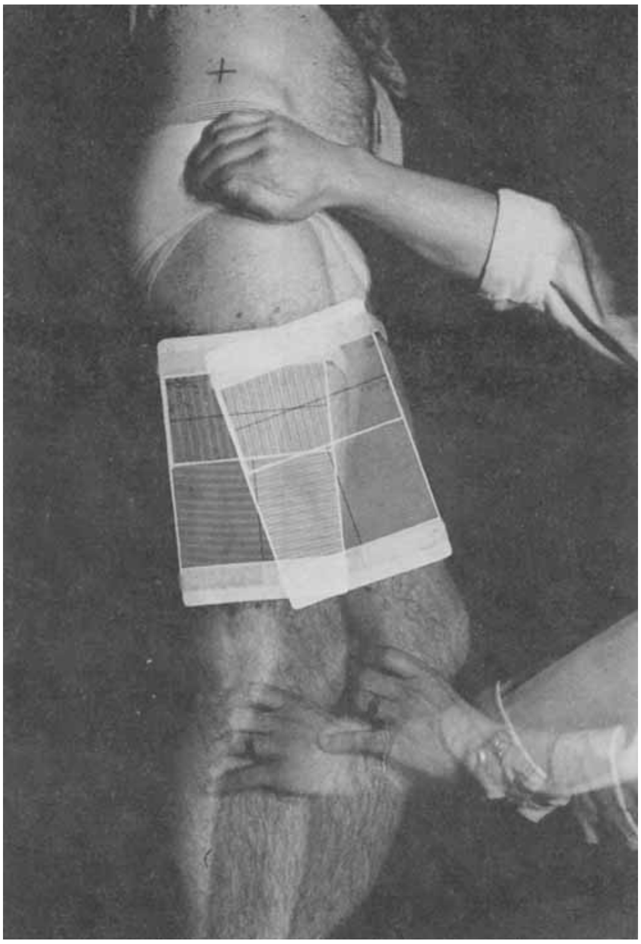

Fig. 7. Typical interference fringes obtained with double exposure of a grid fixed to the thigh, at two positions of the thigh

the distance of the bones from the skin does not alter greatly during the activity. Then the tibia was placed such that at its proximal end the tibial tuberosity was two or three millimetres below the skin at the corresponding location on the image and thus by locating the distal end of the tibia such that the cylindrical surfaces of this end and that of the ankle joint coincided. The model of the tibia was positioned with respect to the image of the leg as closely as possible to its natural position. In a similar manner, other landmarks were used for positioning both patella and femur. The centre of the hip joint was then determined using the Moiré fringe technique as previously mentioned. Thus it was possible from this model to determine the points of contact between the articular surfaces of the knee joint and the lines of action of the different muscles. It must be mentioned here that the insertions of the hamstrings and rectus femoris into the pelvis had to be approximately located. This was done with the aid of illustrations in the anatomy atlas as well as by examining a skeleton. For ethical reasons it was not possible to obtain any X-rays of the pelvis of the subjects participating in the experiment.

After positioning the bone model on every frame and determining the lines of action of the different muscles, the relevant points on the model were digitized and the data obtained on a paper tape. The data on the forces and the position of the point of application of the force on the foot were digitized for every corresponding frame. The forces acting on the articular surfaces as well as the muscle tensions were then computed using a program that took into account the electromyography information (in a binary form), i.e. whenever a trace indicated that a muscle was quiescent, it was given a zero value in the computation.

Results

The experimental procedure described above was carried out and data were obtained from six male subjects from the 1980–81 final year mechanical engineering students at Leeds University. For three of these the forces were calculated throughout the activity of going into a deep squat and then rising up to a standing position. For the other three, the forces during rising from a deep squat were compared for two consecutive runs, one was fast and the other slow. Table 1 presents the distribution of weight, height, and the type of experimental procedure adopted with the different subjects.

Tables 2–4 present the maximum knee joint and muscle forces recorded during experiments.

Figure 8 shows graphs of the variation of these forces with the knee angle (angle of extension) for subject No. 3 when rising quickly from a deep squat, and ascending.

Figure 9 shows graphs of the forces generated during slow and fast ascents from a squat. All of the graphs shown are typical of the results obtained.

Discussion

This study of the forces in the knee joint during the activity of rising from a deep squat was confined to a minimum angle of about 30°. This was due to the contact and consequential pressure between the hamstring and the two gastrocnemius heads in a deep squat obviously having a marked effect on the knee forces. However, in the phase studied some interesting results were obtained and comparisons made.

In general the results showed that the forces computed tend to fall as the leg is extended. The vasti group and the gastrocnemius were always active and the normal tibio-femoral force is always greater than the tangential tibio-femoral force in the activity studied—typically five and three times bodyweight respectively.

Considerable fluctuations occur in the muscle forces, and hence in the joint forces. The phenomenon is probably due to the subject temporarily losing his balance and various muscle controls retaining it. Hence small peaks occur. This type of fluctuation was particularly evident during slow squatting.

Fluctuations also occur because certain muscles are turned ‘on’ and ‘off’. For example when the soleus is found to be quiescent, all the moment about the ankle is supported by the gastrocnemius. It therefore follows that

Table 1. Statistics and type of experimental procedure of the six subjects

Subject No.	1	2	3	4	5	6
Age	21	21	20	21	21	20
Weight, N	750	640	820	630	790	760
Height, m	1.88	1.79	1.85	1.76	1.76	1.78
Slow and fast rise				×	×	×
Fast squat and rise	×	×	×			

Table 2. Summary of maximum joint and muscle forces

Type of activity			Descent to squat			Rise from squat		
	Subject No.		1	2	3	1	2	3
Quadriceps femoris	*Q*	N	4701	4597	5473	4677	5516	4718
muscle force		× BW	6.27	7.18	6.67	6.24	8.62	5.75
Hamstrings	*H*	N	1640	1545	1597	753	1083	802
muscle force		× BW	2.19	2.46	1.98	1.02	1.73	0.99
Gastrocnemius	*G*	N	950	447	1418	631	662	727
muscle force		× BW	1.27	0.712	1.76	0.86	1.05	0.90
Patello-femoral	*P*	N	5555	5159	5650	4827	5898	4649
joint force		× BW	7.41	8.22	7.02	6.56	9.39	5.78
Tibio-femoral joint force	*N*	N	3834	2891	5330	3823	3502	3718
normal to surface		× BW	5.11	4.60	6.63	5.20	5.57	4.62
Tibio-femoral joint force	*D*	N	2913	2340	2703	2224	1868	1815
tangent to surface		× BW	3.88	3.73	3.36	3.02	2.97	2.26

N = force in Newtons
× BW = force as expressed as a multiple of body weight

Table 3. Summary of maximum joint and muscle forces

Type of activity			Slow rise			Fast rise		
	Subject No.		4	5	6	4	5	6
Quadriceps femoris	*Q*	N	3421	2877	3382	4136	3564	3637
muscle force		× BW	5.43	3.64	4.46	6.57	4.51	4.78
Hamstrings	*H*	N	782	639	715	922	677	933
muscle force		× BW	1.26	0.83	0.92	1.49	0.87	1.20
Gastrocnemius	*G*	N	661	1058	541	617	897	640
muscle force		× BW	1.07	1.36	0.77	1.00	1.16	0.83
Patello-femoral	*P*	N	2759	2732	3404	3576	3179	3792
joint force		× BW	4.46	3.53	4.38	5.79	4.0	4.89
Tibio-femoral joint force	*N*	N	3065	3106	3660	3647	3335	3618
normal to surface		× BW	4.96	4.01	4.72	5.90	4.30	4.57
Tibio-femoral joint force	*D*	N	2580	1620	2082	2935	1898	1816
tangent to surface		× BW	4.17	2.09	2.68	4.75	2.50	2.34

N = force in Newtons
× BW = force expressed as a multiple of body weight

Table 4. Summary of average joint and muscle forces

Type of activity			Fast rise	Slow rise	Fast descent	Slow descent
Quadriceps femoris	*Q*	N	4315	3592	5035	4701
muscle force		× BW	6.05	4.94	6.93	5.27
Hamstrings	*H*	N	883	722	1571	1640
muscle force		× BW	1.26	1.01	2.22	2.19
Gastrocnemius	*G*	N	708	723	932	950
muscle force		× BW	0.99	1.00	1.24	1.27
Patello-femoral	*P*	N	4219	3430	5404	5555
joint force		× BW	5.99	4.73	7.62	7.41
Tibio-femoral joint force	*N*	N	3564	3413	4110	3834
normal to surface		× BW	5.01	4.72	5.62	5.11
Tibio-femoral joint force	*D*	N	2056	2126	2521	2913
tangent to surface		× BW	2.96	3.00	3.55	3.88

N = force in Newtons
× BW = force expressed as a multiple of body weight

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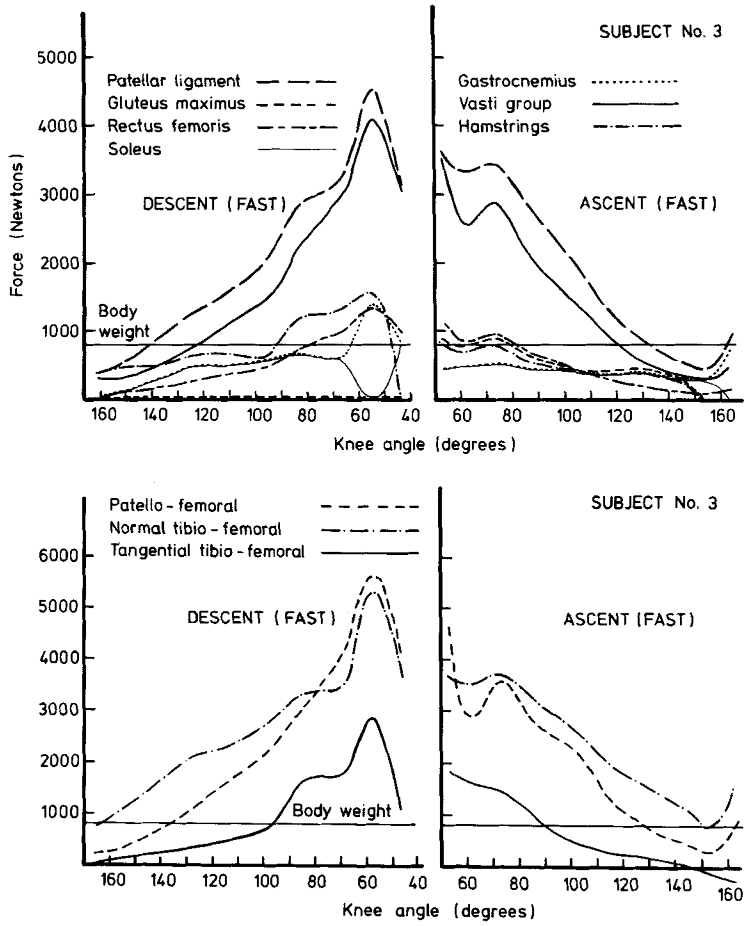

Fig. 8. Computed joint and muscle forces during descent and ascent. The knee angle is defined in Fig. 1

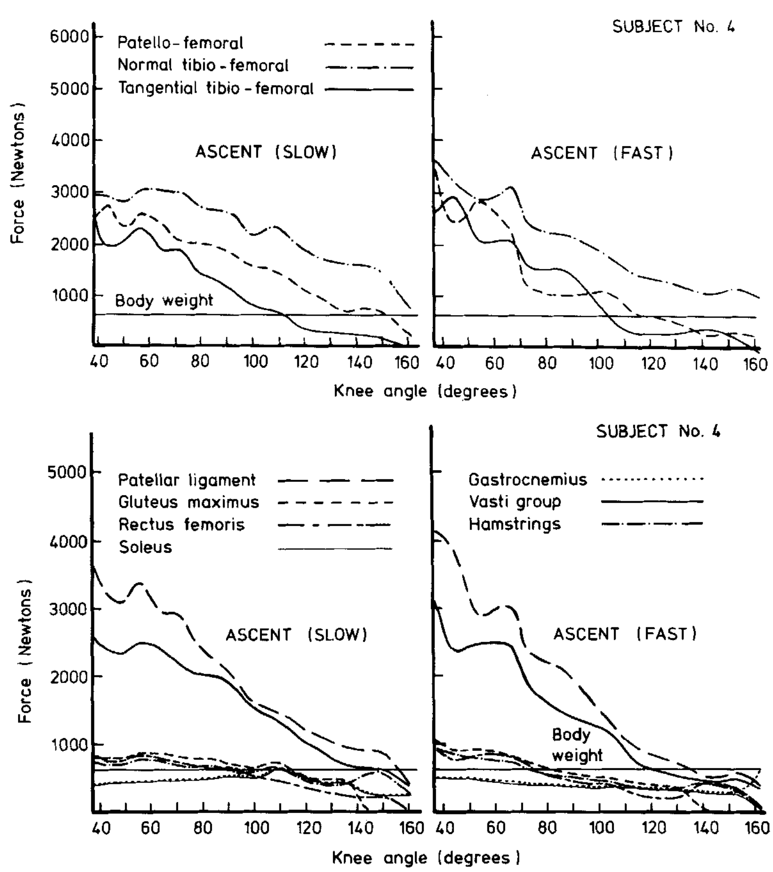

Fig. 9. Comparison of forces during fast and slow ascents. The knee angle is defined in Fig. 2

if the soleus is 'turned off' the force in the gastrocnemius will also increase, and thereby also the force in the knee joint. For example, during the fast descent of subject No. 3, at about 70° of extension both the soleus and gastrocnemius were exerting a force of 600 N whereas the force in the soleus decreased to zero at 65°. To compensate, the force generated in the gastrocnemius reaches a peak of 1400 N. At the same time the joint forces reach a peak (see Fig. 8). This also often happened when the legs were almost fully extended and the forces were at a minimum. A similar situation exists with hamstrings and gluteal muscles.

The forces in a fast rise are not always higher than in the slow rise throughout the activity. During a fast rise an initial peak occurs, generally higher than for the slow rise, followed by a rapid decline in the joint forces. This initial 'kick' gives the body momentum and subsequently less force is required to complete the rise. This is not the case with the slow rise, where the 'kick' is less marked.

It is interesting to note that the joint forces computed, though generally higher for the fast squat, are not very different from the slow activity. The same applies to ascent and descent. This can partly be explained by the fact that more muscles were found to be quiescent in the low load activities, resulting usually in a higher joint force. If, for example, the gluteal muscles or the soleus are inactive, higher forces will have to be generated in the hamstrings and gastrocnemius respectively, resulting in a higher knee joint force. The EMG equipment was therefore found to be particularly important.

Also interesting is the fact that such varying results were obtained. The reasons for this were considered primarily to be due to the subject's varying posture during the activity, but also due to the subject's varying anthropometric measurements. By using the tailor-made models of the leg these differences were catered for. It was found that the position of the patella, the point of contact with the femur in particular, varied from subject to subject. Although the differences were not great, this had a marked effect on the calculated joint forces. A similar situation exists at the point of contact between the femur and tibia. It was therefore considered vital that an accurate tailor-made model be constructed for each subject.

It is evident from the graphs that a larger maximum force occurs in the patellar ligament (which is the main contributor to the normal joint force) when descending rather than rising. The reason for this phenomenon was assumed to be due to the body achieving a larger momentum when descending as opposed to rising. Therefore a larger 'kick' is required to decelerate the body in the squat.

The role of the cruciates during the activity was also investigated. Computations were made of the forces transmitted through these ligaments. Whilst down in a deep squat the anterior cruciate is at a very large angle to the surface of the tibia. If this ligament is then assumed to take all the tangential load, a very large force will be generated in the cruciate. This leads to the conclusion that tangential load is transmitted through other structures, for example the menisci, the collateral ligaments and the concavity of the tibial condyles. There is, however, no doubt that the cruciates, the anterior cruciate in particular, do in fact bear some of the tangential force. It must be borne in mind then, that an additional normal load will be induced by the cruciate because it has a force component normal to, as well as tangential to the surface. The exact amount will require further research into the mechanics of tangential load transmission, in the knee

Conclusions

1. Widely varying joint forces were discovered. The patello-femoral forces computed were the largest, the average maximum values varying between 4.7 times bodyweight (slow ascent) and 7.6 for the fast descent.
2. The forces normal to the tibio-femoral joint surfaces varied between 4.7 to 5.6 times bodyweight. Tangential to the joint surface the figures varied from 2.9 to 3.5 times bodyweight.
3. Differences in the joint forces may be attributed to the varying posture in the subjects, and also to the varying anthropometric measurements. A tailor-made model was therefore considered vital.
4. The results show fluctuating muscle forces, and hence joint forces. Apart from jerks caused by temporary loss of balance, some of the undulations may be attributed to muscle activity. EMG was found to be particularly important. The variation in muscle activity between subjects was large.

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