

Strategies of muscular support of varus and valgus isometric loads at the human knee

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Abstract

In this paper we studied how subjects activate their muscles in response to static varus and valgus loads at the knee. The muscles' contributions to the external moments were estimated using an EMG driven biomechanical model of the knee. The individual muscle activation and loading patterns were examined to identify the strategies that the nervous system uses to support varus and valgus knee moments. It was found that the (1) co-contraction of the hamstrings and quadriceps, and (2) activation of the gracilis and tensor fascia lata increased with the increasing magnitude of the varus and valgus moments. These 2 activation patterns provided positive support of valgus and varus loads at the knee, whereas during varus moments this muscle increases the varus load on the knee, i.e. provides negative support. Generally, the hamstrings and quadriceps co-contraction contributed to most of the muscular support of the varus and valgus moments. In addition, co-contraction supported 11–14% of the external moment in pure varus and pure valgus respectively. It appears that there are activation strategies with the specific purpose to support varus and valgus moments, albeit small, which suggest dual goals of the neuromotor system during the support of varus and valgus moments. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Varus and valgus; Knee; muscle moment contribution; Activation patterns

1. Introduction

Large forces on the articular surfaces of the knee during varus or valgus loading are thought to be the principal factors in the development of osteoarthritis (Kettelkamp et al., 1988; Schipplein and Andriacchi, 1991; Noyes et al., 1992). Muscles and ligaments control how the total joint force is shared between the articular surfaces. In addition, cadaver studies and biomechanical models have shown that muscles can support varus or valgus (VV) moments at the knee by concurrent support of flexion or extension (FE) moments thus potentially unloading the knee ligaments, especially the collaterals (White and Raphael, 1972; Goldfuss et al., 1973; Schipplein and Andriacchi, 1991; Noyes et al., 1992). This potential for muscles to unload ligaments does not

imply that people actually activate their muscle to do so. Lloyd and Buchanan (1996) have recently shown that, in total, muscles are activated to support about 15% of the static pure VV external loads, and that the muscular contribution increased as subjects supported more flexion or extension moments.

The question then arises; what particular activation strategies produced this support of VV moments, and what are the contributions from these patterns? Andriacchi et al. (1984) have shown that muscles may be activated to support an externally applied VV moment, but identified no muscle activation strategies used to support VV moments. The sartorius, gracilis and tensor fascia lata have substantial VV moment arms. Buchanan and Lloyd (1997) showed that the gracilis and tensor fascia lata had activation patterns more directed to stabilize the knee in varus and valgus respectively. However, given the small cross-sectional area of these muscles, could the levels of activation observed explain the 15% level of support provided by all muscles during

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pure VV loading? Since the quadriceps and hamstrings have VV moment arms, co-contraction of these muscles may stabilize the knee in VV (Schipplein and Andriacchi, 1991). However, little evidence was found for hamstrings and quadriceps co-contraction in the study by Buchanan and Lloyd (1997). It could be that analyses performed were not the most suitable to detect any co-contraction strategy.

Generally the ligaments of the knee become more taut when the knee is in more extended postures (Markolf et al., 1976; Blankevoort et al., 1991; Markolf et al., 1995) and could be more highly stressed when the knee is externally loaded. For example, when the knee is in less than about 40° flexion the anterior cruciate ligament can be quite highly loaded when external VV loads are applied (Markolf et al., 1995). Lloyd and Buchanan (1996) showed that the muscular contribution to the external VV moments increased when the knee was more extended which would most probably reduce stresses in all knee ligaments. Is this the result of specific activation patterns, or purely related to joint mechanics?

In this paper we investigated the activation strategies used by individuals to support VV moments and the muscle loading patterns that result from these activation schemes during highly controlled isometric tasks. Specifically, the following questions were addressed. (1) To what extent does co-contraction of quadriceps (QUADs) and hamstrings (HAMs) play a role in supporting VV loads? (2) To what extent do the different muscle activation strategies contribute to VV moments? (3) To what extent do muscle activation patterns and/or joint mechanics cause the increased support of varus/valgus moments as the knee extends?

2. Methods

2.1. Experiments

The experiments performed have been described in detail previously (Lloyd and Buchanan, 1996; Buchanan and Lloyd, 1997) and will be briefly presented below. Ten healthy young males participated in the study and gave their informed, written consent prior to starting the experiments. They had no history of knee degeneration and were selected to be all of similar build (age 28.9 ± 5.5 years; height 1.80 ± 0.07 m; weight 81 ± 6.4 kg) to the anatomical model used in the biomechanical model of the knee.

In all trials each subject was free to abduct or adduct the hip but was allowed no abduction or adduction movement at the knee. The ankle was also flail in all trials. The subject's shin was cast into a six component load cell and using visual feedback, were instructed to produce forces radially in the traverse plane at the load cell with 20° between force directions (Fig. 1A). All forces were of the same magnitude and imposed combinations of flexion and extension and varus and valgus moments onto the knee with a constant magnitude of 23.0 ± 7.5 N m (mean \pm standard deviation from the 10 subjects). The four repetitions of each force direction were presented in random order and all performed at knee flexion angles of 40°, 50°, 60°, 70°, 80° and 90°. To negate the effects of fatigue, the subjects had regular periods of rest and the order of knee flexion angles was randomly chosen.

The electromyographs (EMG) were recorded from the semitendinosus (ST), biceps femoris long head (BFL),

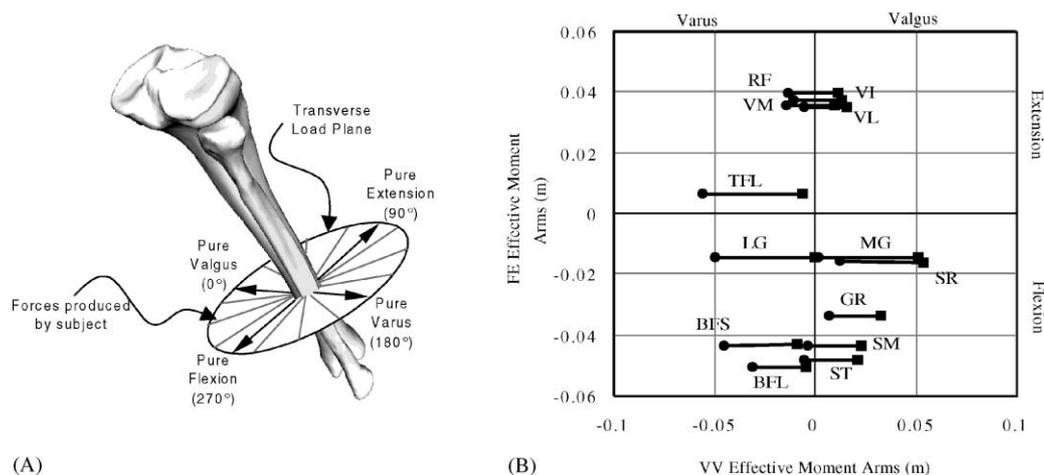


Fig. 1. (A) Schematic of the forces produced in the transverse load plane. These forces map into combinations of varus–valgus and flexion–extension moments at the knee. For example, a force produced with a direction between pure extension and pure varus (from 90° to 180°) will map into a moment at the knee that has extension and varus components. (B) The moment arms of the muscles of the knee at 40° knee flexion angle. Shown are each muscle's varus or valgus and flexion or extension moment arms. The ● indicates moment arms about the medial condyle and the ■ indicates moment arms about the lateral condyle. It is assumed that varus moments occur about the medial condyle and valgus moments about the lateral condyle. Thus a muscle with a varus moment arm can resist/support a varus moment and valgus moment arm a valgus moment.

vastus lateralis (VL), vastus medialis (VM), rectus femoris (RF), tensor fasciae lata (TFL), gracilis (GR), sartorius (SR), and medial and lateral gastrocnemius (MG and LG). The EMG from SR, GR, and TFL were recorded using pairs of fine wire intramuscular electrodes and the remainder of the muscles were recorded using bipolar surface electrodes. All EMG signals were collected on a computer and processed to create each muscle's normalized trial EMG (ε), of which the values ranged between 0 and 1. The load cell data were also collected on the computer and the static hip, knee and ankle angles measured using a goniometer (Lloyd and Buchanan, 1996; Buchanan and Lloyd, 1997).

2.2. Biomechanical model

The biomechanical model of the knee employed is described in detail in Lloyd and Buchanan (1996). To briefly summarise, the biomechanical model consisted of an anatomical model and an EMG driven Hill-type musculo-tendon model to estimate muscle forces. In the anatomical model (Lloyd and Buchanan, 1996), developed in software for interactive musculoskeletal modelling (SIMM[©]-Musculographics, Chicago, IL, USA) (Delp et al., 1990), there were 13 muscles represented, the 10 muscles from which EMGs were recorded plus the vastus intermedius (VI), semimembranosus (SM) and biceps femoris short head (BFS). The anatomical model provided the muscle moment arms and musculo-tendon lengths for each of the muscles.

For reference, typical moment arms of the muscles used in the model, at 40° knee flexion, are depicted in Fig. 1B. The magnitudes of these change with joint angle, but whether each muscle has a varus or valgus moment arm, with very few exceptions, does not change with joint angle. Whether a muscle is flexor or extensor does not change with joint angle. Throughout this paper a muscle is said to have a varus moment arm if it can resist/support a varus knee moment or a valgus moment arm if it can support a valgus knee moment. In addition, a muscle is said to have a flexion moment arm if it generates knee flexion, and an extension moment arm if it generates knee extension.

Muscles were characterized by a normalized length-tension relationship and tendons by a normalized non-linear force-length relationship (Zajac, 1989). The forces generated by musculo-tendon units were determined using muscle activation and musculo-tendon lengths as inputs. Each muscle's activation was assumed to be equal to the average ε . The activation of the VI was assumed to be average of the VL's and VM's activation, the ST's activation the same as the SM's activation, and BFS's the same as the BFL's.

To account for subject variability, each subject's muscle parameters (i.e. optimal fibre lengths, tendon slack lengths, and specific muscle stress for flexors and

extensors) were adjusted within physiological bounds. The calculation of these bounds were described in Lloyd and Buchanan (1996) and were based on the averages and standard deviations of muscle-tendon architectural data published in a number of studies (e.g. Yamaguchi et al., 1990; Delp et al., 1990; Hoy et al., 1990; Herzog et al., 1990). The parameters were adjusted using a non-linear least-squares method to ensure that the model accurately predicted the experimental flexion and extension moments generated by each subject in each of the trials. Once the muscle parameters, and hence muscle forces, were established, the muscular and non-muscular soft tissue contributions to external varus and valgus moments were estimated.

2.3. Analysis

The main purpose was to assess the potential for the different knee muscles to support varus and valgus moments. This potential is dependent on the muscles varus and valgus moment arms and on how the muscles were activated. Subsequently, based on the results from our previous paper (Buchanan and Lloyd, 1997), the HAMs (BFL, BFS, ST, SM) and the QUADs (RF, VM, VI, VM) were grouped into functional units because of these muscles' strongly directed activation patterns towards flexion and extension (see Fig. 3A in Buchanan and Lloyd, 1997). The TFL, GR, SR, MG and LG were all analysed separately based on their directed activation patterns to support varus and/or valgus moments (see Fig. 3B. in Buchanan and Lloyd, 1997), and/or large varus/valgus moment arms (Fig. 1B).

The summed activation of HAMs and QUADs was calculated by adding the average ε of the muscles in each group. The subject average and standard deviation of the HAMs and QUADs summed activations were calculated across knee joint angles at each moment direction.

For the HAMs, QUADs and other individual muscles the principal direction and magnitude of activation in the transverse plane was determined based on the sum of the EMG vectors (Buchanan and Lloyd, 1997). Here, each datum of ε in the flexion-extension-varus-valgus plane was treated as a vector and these were then vectorially added to produce an activation vector whose direction corresponded to the mean direction of activity of the muscle. The normalized magnitudes of the activation vectors were also calculated by dividing vector magnitudes at each knee angle by the maximum magnitude observed from all knee angles.

The co-contraction ratio (ρ) of the HAMs and QUADs was calculated as the ratio of the HAMs' summed activation and the QUADs' summed activation at each moment direction. The HAMs' activation was chosen as the divisor if its value was greater than the QUADs and the QUADs' activation the divisor if its

value was greater than the HAMs. Therefore, the ρ was always less than or equal to 1. The principal direction and magnitude of co-contraction in varus was determined by treating each ρ in flexion-varus-extension half-plane as a vector and then summed to create the varus co-contraction vector (ρ_{varus}) whose direction and magnitude corresponded to the mean direction and magnitude of co-contraction in varus. Similarly, the principal direction and magnitude of co-contraction in valgus, the valgus co-contraction vector (ρ_{valgus}), was determined using the co-contraction ratios in flexion-valgus-extension half-plane. The magnitudes of the co-contraction vectors were normalized by dividing the vector magnitudes at each knee angle by the average from all knee angles.

Muscle contributions to the external VV moments were determined using the biomechanical model of the knee. The VV moments supported by the HAMs and QUADs were calculated by summing the moments supported by the muscles in each group. The total VV muscle moments were also calculated. The subject averages and standard deviations of the VV muscle moments were calculated (1) at each knee joint angle and moment direction, and (2) in pure varus and pure valgus averaged across the knee joint angle.

It was apparent that the MG contribution to the VV moments was different depending on the subjects. Eight of the ten subjects had very low MG valgus moments, called Group1, whereas two of the subjects had large MG valgus moments called Group2. This dichotomy did not exist in the other muscle groups.

The differences between moments generated by the HAMs and QUADs and the other individual muscles in pure varus and pure valgus was evaluated using Data Desk statistical software (©Data Description, Ithaca, NY, USA). The statistical model was a three factor repeated measures ANOVA (factor 1—varus or valgus, factor 2—group: Group1, Group2, factor 3—muscle: HAMs+QUADs, TFL, GR, SR, LG, MG) with LSD post hoc tests. The co-contraction of the QUADs and HAMs at pure varus and valgus could have been to just overcome the FE moments produced by TFL, GR and SR muscles, which may have been activated to abduct or adduct the hip. The difference in the FE moments produced by these muscles in pure varus and pure valgus was tested using a single factor repeated measures ANOVA (factor—muscle group: HAMs, QUADs, TFL+GR+SR) with LSD post hoc tests.

3. Results

The HAMs and QUADs were mostly activated to support flexion or extension moments (Fig. 2A and 3C) related primarily to these muscles FE moment arms (see Fig. 1B). However, these muscles did exhibit overlap in

their activations towards pure varus and pure valgus (Fig. 2A). This overlap means that these muscles were co-contracted (Fig. 2B), i.e., the HAMs were activated while the subjects were generating extension moments and the QUADs were active during flexion moments. This co-contraction reduced to negligible levels towards

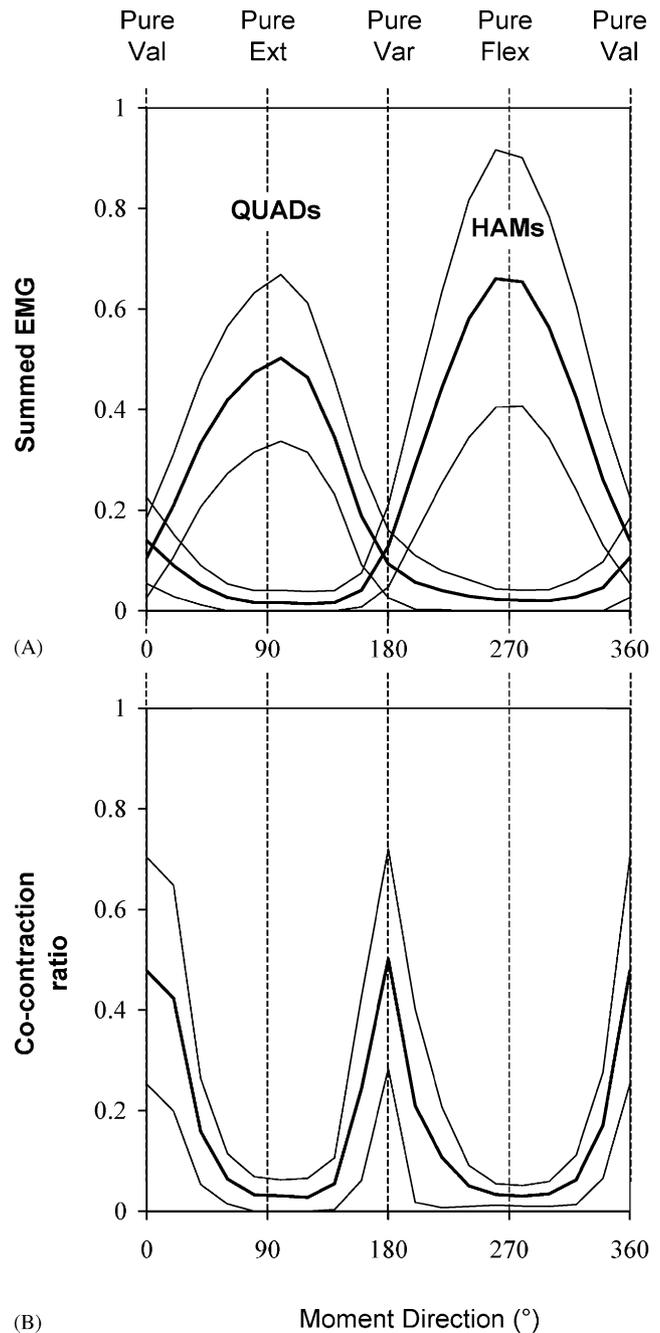


Fig. 2. The (A) activation HAMs and QUADs, and (B) co-contraction ratio of these muscles plotted versus moment direction for the knee flexion angle of 50°. The pattern of the HAMs and QUADs activation and co-contraction was very similar at other knee angles. The values shown are the subject averages (dark lines) and standard deviations (light lines).

pure flexion or pure extension. The principal co-contraction directions (Fig. 3D) during varus moments were very close to pure varus (180°) and during valgus moments very close to pure valgus (360°). In varus the co-contraction magnitudes decreased as knee became more extended, whereas in valgus the co-contraction magnitudes remained constant across all knee angles (Fig. 3H).

The HAMs and QUADs supported the majority of the VV moments (Figs. 4A and 4B). The TFL and GR muscles had much smaller contributions in comparison (Fig. 4C) and the SR had negative contributions to varus moments and positive contributions to valgus moments (Fig. 4D). In the eight subjects of Group1, the peak VV support provided by all the knee muscles was around either pure flexion or pure extension (Fig. 5C), with a minimum around pure varus and pure valgus. This pattern was dictated primarily by the actions of the HAMs and QUADs (Figs. 4A and 4B), as these muscles were activated towards flexion and extension (Figs. 2A and 3C), and thereby produced more force and supported more of the external VV moment. In Group1 the total muscle contribution to the pure varus moments was $17 \pm 9.7\%$ and pure valgus moments was $10 \pm 6.3\%$.

In the two Group2 subjects, the large HAMs and QUADs VV support around pure flexion or pure extension was still observed (Fig. 5D), but the dominant action of the MG around pure valgus was evident (Figs. 5B and 5D). Compared to Group1, these two subjects generated larger muscle moments in pure varus and valgus; 23% and 53% respectively.

The muscular support in the pure varus and pure valgus loading conditions was largely determined by the co-contraction of the HAMs and QUADs (Fig. 7) with smaller contributions by the other muscles. The HAMs and QUADs contribution in pure varus was larger than the other muscles groups ($p < 0.001$, except TFL with $p < 0.025$). For all subjects in pure varus the combined action of the HAMs and QUADs (HAMs+QUADs) supported approximately 14%, the TFL, GR, LG and MG muscles contributed an additional 5.5%, while the SR had negative 1% contribution. For all subjects in pure valgus the HAMs+QUADs produced more moments than each of the other muscles ($p < 0.001$), with the exception of the MG in Group2 (Fig. 7). Additionally, in the pure varus and pure valgus the level of the QUADs and HAMs co-contraction more than balanced the combined FE actions of the TFL, GR and

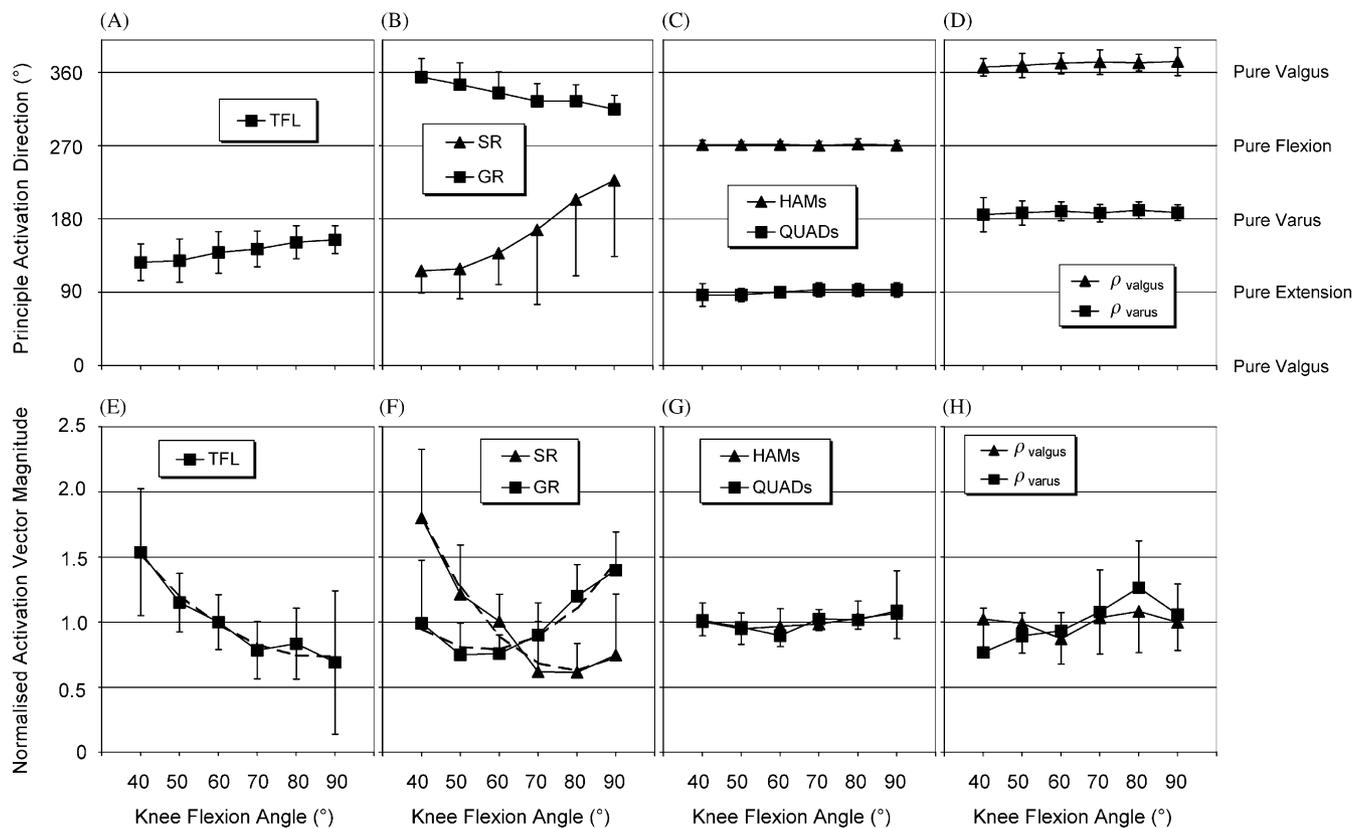


Fig. 3. The principal activation directions for the (A) TFL, (C) SR and GR, (B) HAMs and QUADs, and (D) HAMs and QUADs co-contraction ratios, ρ_{valgus} and ρ_{varus} . Also shown are the normalized activation vector magnitude for the (E) TFL, (F) SR and GR, (G) HAMs and QUADs, and (H) ρ_{valgus} and ρ_{varus} . The dashed lines in (E) and (F) are the least squares quadratic fit to the activation magnitude data for the TFL, SR and GR. All values shown are the subject averages and standard deviations at the different knee flexion angles.

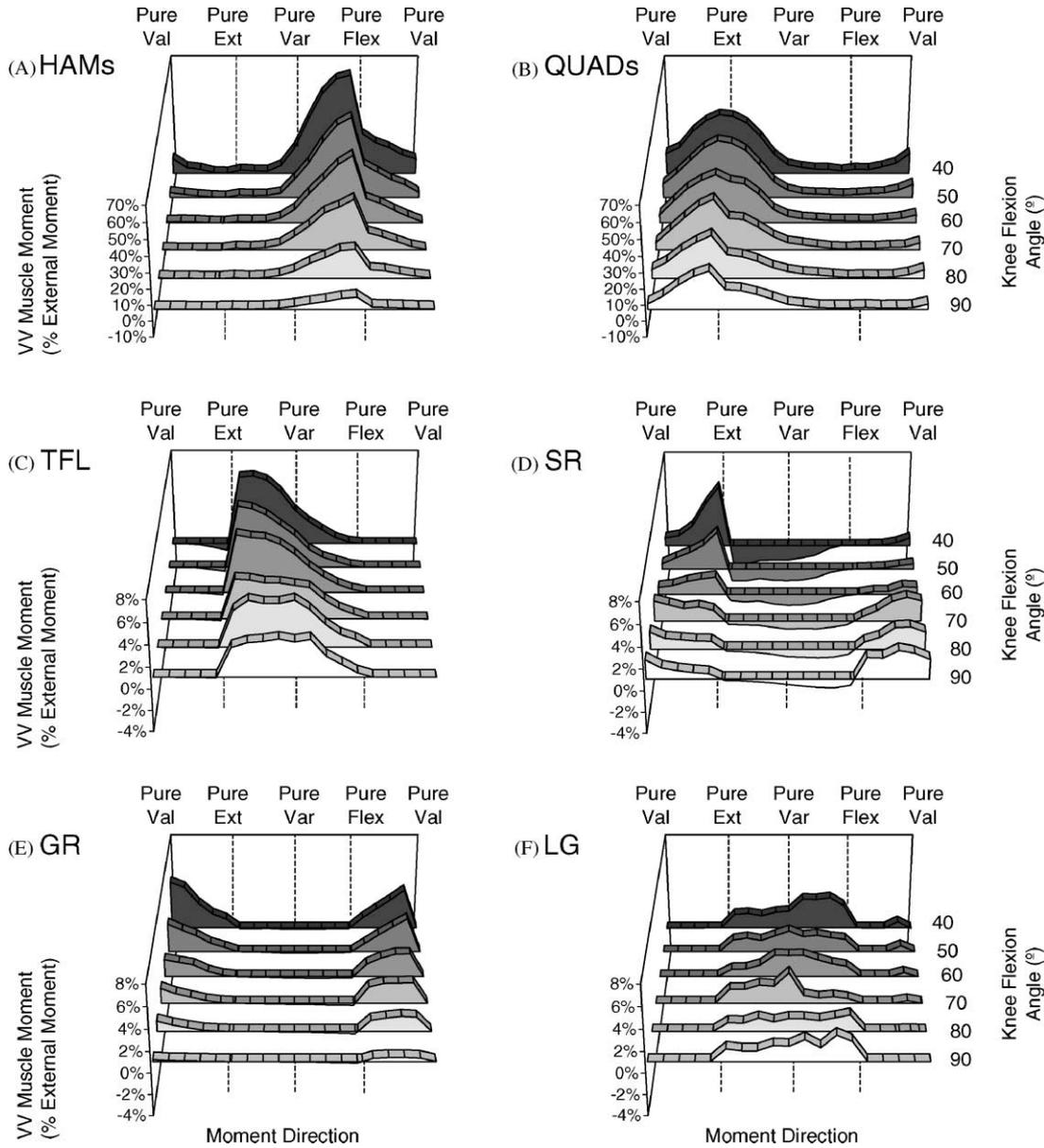


Fig. 4. The contributions to the external VV moment by the (A) HAMs, (B) QUADS, (C) TFL, (D) SR, (E) GR, and (F) LG. All values are subject averages expressed as a percentage of the total external moment at the different knee flexion angles.

SR at the knee, when respectively the HAMs had 11.4 times larger and QUADS a 10.0 times larger ($p < 0.001$) FE contribution than the combined FE moment produced by the TFL, GR, and SR.

The activation patterns of the gastrocnemi were quite erratic between subjects. The principal activation directions, averaged across knee angle, were $202 \pm 79^\circ$ and $189 \pm 65^\circ$ for the MG and LG respectively, note the large standard deviations. Nevertheless, the LG provided a small level of varus moment support (Fig. 4F), corresponding with its large varus moment arm when the knee had varus moments applied (Fig. 1B). In Group1 the MG generated small levels of varus moments support (Fig. 5A). However, the MG in

Group2 produced large valgus moment support (Fig. 5B), and in pure valgus the MG-Group2 support was much larger than each of the other muscles ($p < 0.01$), apart from the HAMs+QUADS (Fig. 7), for which the small number of subjects would have affected this significance level. This result, however, shows the potential for the MG to provide valgus moment support.

The VV support by all muscles, except LG, increased when the knee was moved into more extended postures (Figs. 4 and 5) and was due to the average VV moment arms of the muscles increasing with decreasing knee flexion angle for all muscles except the TFL (Fig. 6A). When flexed at 90° , the varus and valgus components of

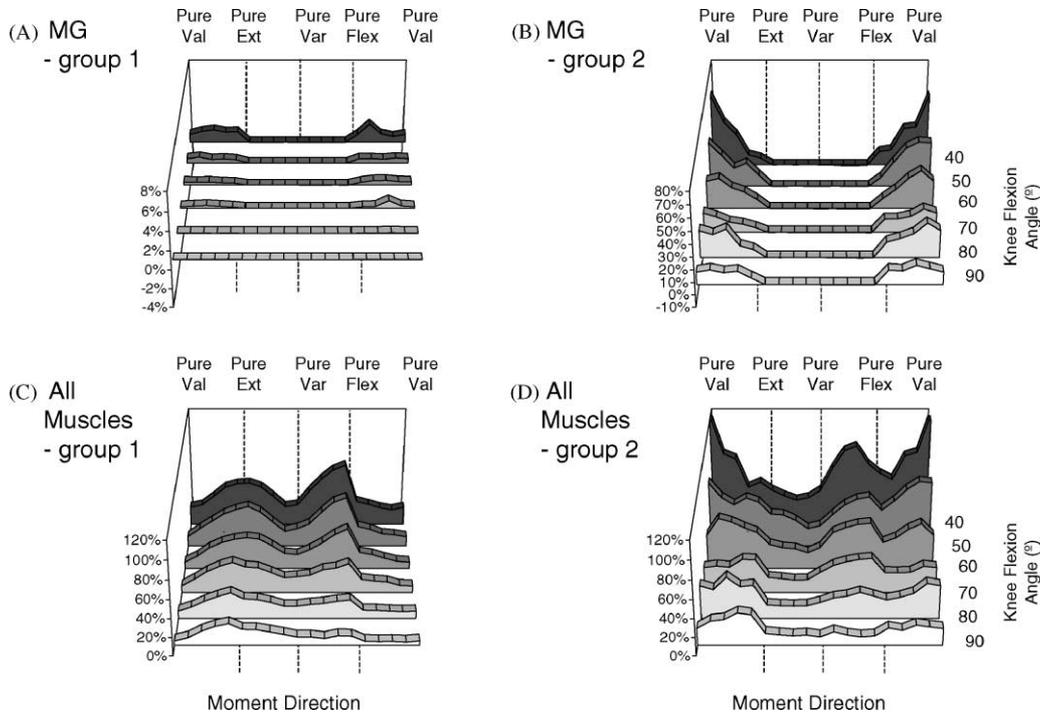


Fig. 5. The contributions to the external VV moment by the MG from subjects in (A) Group1 and (B) Group2, and from all muscles in (C) Group1 and (D) Group2. All values are subject averages expressed as percentage of the total external moment at the different knee flexion angles.

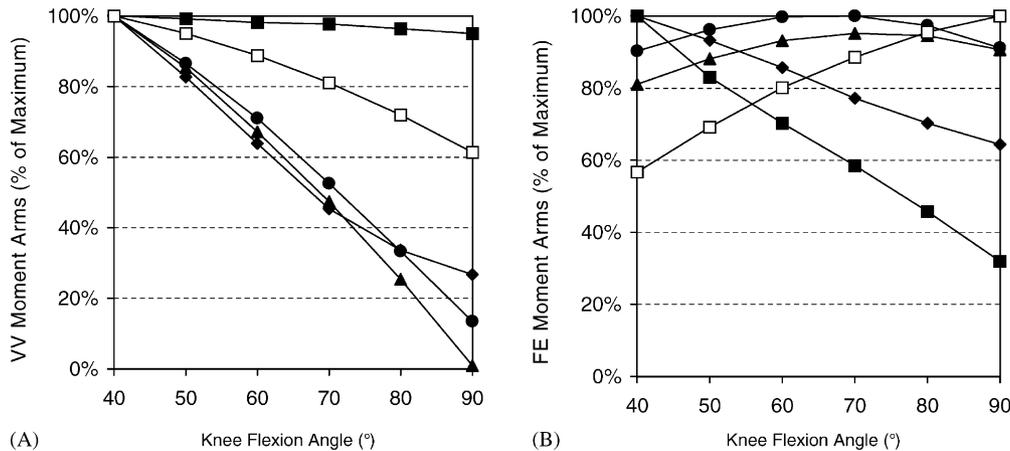


Fig. 6. The average (A) VV moment arms, and (B) FE moments arms for the ▲—HAMs, ◆—QUADs, ■—TFL, ●—GR, and □—SR plotted versus knee flexion angle. The values are expressed as a percentage of the maximum effective VV and FE moment arms respectively in the range of knee flexion angles used in the experiments.

the moment arms decrease to less than 60% of their values at 40°. In addition, the VV muscle moments were calculated using each muscle’s VV moment arms averaged across knee angle and compared with VV muscle moments calculated with the normal VV moment arms. The Pearson correlation between the two was -0.24 , which reveals the large effect of VV moment arm on the muscular support of the VV moments.

The role of muscle activation magnitude to dictate the level of VV support was apparent in only the TFL and GR. The activation magnitudes of the QUADs and

HAMs did not change across the knee angle (Fig. 3G), so the VV support by the QUADs and HAMs co-contraction was mainly dependent on the increase of these muscles VV moments arms as knee was extended (Fig. 6A). However, the increased contributions from the TFL and GR as the knee extended, was a result of the increases in the levels of activation (Figs. 3E and 3F). The TFL varus moment arm did not increase as substantially as the other muscles (Fig. 6A), but the normalized activation magnitude increased quadratically ($\epsilon_{TFL} = 3.40 - 0.062\theta_K + 3.57 \times 10^{-4}\theta_K^2$; $R = 0.85$)

with decreasing knee flexion angle (θ_K) (Fig. 3E). The GR activation magnitude also changed quadratically ($\varepsilon_{GR} = 5.47 - 0.123\theta_K + 7.85 \times 10^{-4}\theta_K^2$; $R = 0.91$) with the knee angle (Fig. 3F), with the minimum at around 57° flexion with increasing activation from 57° flexion to 40° flexion.

4. Discussion

In the following, the three questions posed will be addressed. In answer to the first question, the results show that there was directed co-contraction of the HAMs and QUADs to support the VV moments at the knee. Was this pattern due to the action of the muscles at the hip? The subjects could only generate the varus and valgus moments at the knee by hip abduction and adduction respectively. The other biarticular muscles (TFL, GR and SR) may have been activated to produce the hip abduction/adduction and the FE action of these muscles at the knee may have been balanced by HAMs and/or QUADs activation. However, it was shown that the HAMs and QUADs contribution to the knee FE moment was much larger than the combined contribution by the other biarticular muscles during the pure varus/valgus loading conditions, and were probably not activated to balance the action of the other biarticular muscles. The uniaxial QUADs could have also been activated to balance the FE moments produced by the biarticular HAMS and/or rectus femoris that may have been activated to generate abduction/adduction or internal/external rotation hip moments. If the HAMs and rectus femoris were activated to generate these moments then you would expect that the activation patterns of these muscles would show directionality towards varus or valgus. However, this was not the case, with the activation of these muscles strongly directed towards pure flexion or pure extension (see Fig. 3C and 3A in Buchanan and Lloyd, 1997). Thus it is postulated that the directed HAMS and QUADs co-contraction towards varus and valgus was a strategy that the neuromuscular system used to stabilize the knee.

It is suggested that there are two specific activation strategies that the neuromuscular system uses to support VV moments at the knee. These are (1) the co-contraction of the HAMs and QUADs and (2) tuned activation of the GR and TFL towards the support of the VV loads (Buchanan and Lloyd, 1997). As a consequence of using the HAMs and QUADs, when the external load has increasing extension and flexion components, the general strategy is to change to one where the support of the FE moment becomes the dominant factor dictating activation and VV moment support.

As suggested by Buchanan and Lloyd (1997) the TFL and GR appear to be activated to support varus and

valgus moments respectively. However, this needs to be qualified. The TFL activation increased as the knee extended (Fig 3E) assisting varus moment support. However, the activation of the TFL, at least at the more extended knee angles examined, could have been driven by the muscle's extension moment arm. This is seen when the knee is closer to full extension and the TFL's extension moment arm becomes larger (Fig. 6B), the principal activation was redirected closer towards pure extension away from pure varus (Fig. 3A). Nevertheless, there was sufficient spread of the activation of the TFL to support moments in the load directions with large varus components (Fig. 4C).

The GR may have been principally activated to support valgus knee moments, especially when the knee was closer to 40° extension. The GR activation patterns may be concordant with the GR hip moments arms (GR is a hip extensor, hip adductor and hip internal rotator) with the knee in the flexed postures, from 60° to 90° , but GR hip moments arms would change minimally when the knee extended. However, in the extended postures the knee moment arms may govern the GR activation pattern. This is observed in the GR activation pattern, which (1) became more directed towards pure valgus as the knee extended, and (2) had increased activation levels with knee flexion angles from 60° to 40° . This pattern would correspond with the increasing valgus moment arm (Fig. 6A) and decreasing flexion moment arm (Fig. 6B) as the knee became more extended.

In answer to the second question, the HAMs and QUADs co-contraction strategy supported most of the pure varus and pure valgus load, except in two subjects. However, the overall muscular support was small at around 11% to 17% of the pure valgus or varus moments. The HAMs and QUADs support of the VV moment increases as the extension and flexion component of the external load increases. The SR did not appear to be activated to support VV moments, which was generally reflected in the moment contributions from this muscle.

The TFL and GR muscles are best suited to counter VV moments by virtue of the large VV moment arms compared to the HAMs and QUADs (Fig. 1B). They also appear to be activated accordingly as discussed above. However, they contribute far less to VV load support compared to the HAMs and QUADs, which are much larger muscles than the TFL and GR. The average physiological cross-sectional area (PCSA) of the TFL and GR is 3.7 cm^2 , whereas the average PCSA of the HAMs and QUADs is 21.7 and 14.1 cm^2 respectively (calculated from the data in Yamaguchi et al., 1990).

The above conclusion regarding the dominance of the HAMs and QUADs VV support needs to be tempered since the foot was flail in the current experiments. This may account for the very low and erratic activation and VV support of the gastrocnemi in most of the subjects (8

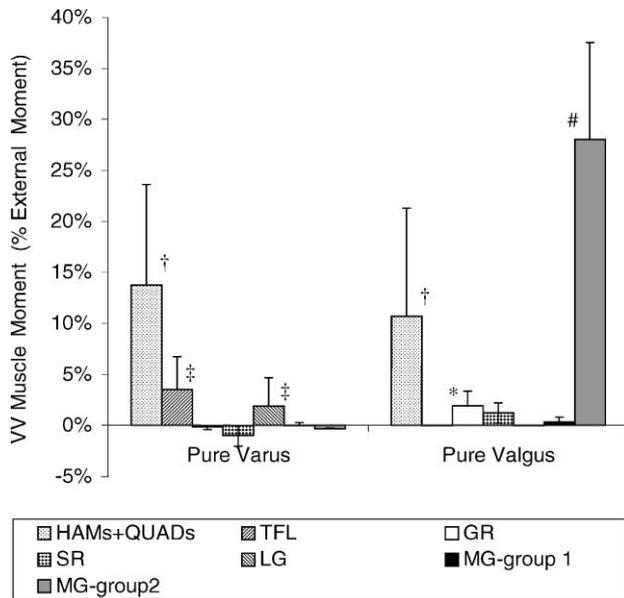


Fig. 7. Shown are the muscle VV moments (% external moment) during pure varus and pure valgus loading. The values shown are the subject averages and standard deviations averaged across knee joint angle. †HAMs+QUADs varus and valgus moments significantly larger than each of the SR, TFL, GR, LG, and MG ($p < 0.001$, except TFL with $p < 0.025$ in pure varus); ‡TFL and LG varus moments significantly larger ($p < 0.001$) than each of the GR, SR, and MG; *GR and SR valgus moments significantly larger than each of the TFL and LG ($p < 0.001$), and MG-Group1 ($p < 0.05$); # MG-Group2 valgus moments significantly larger ($p < 0.01$) than all other muscles, except HAMs+QUADs.

out of 10) (Figs. 5A and 7). However, in two subjects the MG activation was such that quite considerable valgus support was generated (Figs. 5B and 7). This support could only be generated by co-contraction of the ankle dorsi-flexors (e.g. tibialis anterior). These results show the importance of accounting for an individual's activation patterns when determining the VV support provided by muscles. These results also suggest that in tasks that require generation of plantar-flexion moments at the ankle joint (i.e. walking) there would be a greater role for the gastrocnemi support of VV moments.

In answer to the third question, joint mechanics are the primary reason for the increased VV moment support as the knee extended. This is due to the large increase in the VV moment arms of all knee muscles except the TFL (Fig. 6A). The VV moment arms are larger at more extended knee angles because the muscles tend to be more perpendicular to the tibial plateau compared to the flexed knee positions. The moment arms become smaller as the knee is flexed because the muscles become more parallel with the VV axis of rotation, which is parallel to the tibial plateau in the posterior to anterior direction. The QUADs VV moment arms depend on the patella-femur-tibia mechanics (Yamaguchi and Zajac, 1989), which gives the best mechanical advantage towards full extension. Thus,

the mechanics of the knee joint and muscles appear to be uniquely designed to support the varus loads during the stance phase of gait, especially when supporting flexion or extension moments at the same time. In addition, given that the knee ligaments generally become more taut as the knee is placed in more extended postures (Markolf et al., 1976; Blankevoort et al., 1991; Markolf et al., 1995), relying mostly on muscle and joint mechanics is simple but effective way to unload ligaments during VV loading.

Muscle activation patterns and joint mechanics determined the level of VV support provided by the TFL and GR. These muscles provided increased VV support as the knee extended, particularly from 60° to 40° knee flexion, in line with the other muscles. For the TFL this was due to increased activation (Fig. 3E) rather than a large increase of the varus moment arm (Fig. 6A). For the GR, as the knee extended the increased valgus support was provided by the increased activation redirected towards valgus (Figs. 3B and 3F) from 60° to 40° knee flexion. Thus it could be concluded that the general goal of neuromuscular control is to increase the VV support as the knee extends, which is caused mainly by mechanics. Where mechanics do not assist in this pattern, the muscle activation may also be increased to compensate.

The experiments performed were only static isometric tasks and very different patterns of muscle activation are likely during dynamic weight bearing. In addition, different activation patterns have been observed in different types of isometric tasks (Buchanan and Lloyd, 1995). However, as shown previously (Buchanan and Lloyd, 1997) in all knee muscles there were graduated changes in the activations tuned to principal directions of activation. This demonstrates that the motor control system is capable of and routinely uses specific muscle activation strategies to stabilize the knee during varus–valgus loading. Therefore, the experiments were well suited to investigate the role of muscles in the stabilization of the knee during varus–valgus isometric tasks.

EMG cross talk between muscles would have little influence on the co-contraction patterns observed. Most of the high levels of co-contraction occurred towards pure varus and pure valgus directions, when the EMG levels for the HAMs and QUADs were low, and where the possibility for cross talk would have been negligible. The use of intramuscular electrodes would mean minimal cross talk in TFL, GR and SR muscles.

With regard to model accuracy, Lloyd and Buchanan (1996) have shown that all model assumptions had very little effect on the estimated soft tissue loadings. The muscle model parameters, were all based on those presented in literature (Delp et al., 1990; Yamaguchi et al., 1990) and were adjusted to be within physiological bounds. In addition, Lloyd and Buchanan (1996)

showed that the adjusted model results were reproducible using a cross validation study.

The muscles were not sufficient to support the VV loads in most load conditions and there was a great dependence on the soft tissues (i.e., ligaments and joint capsule) for VV stabilization (Lloyd and Buchanan, 1996). However, there were directed activation patterns to support the VV loads, even though the muscles were far from being maximally activated to provide the VV support. So the muscles may have been used to unload the soft tissues to a certain prescribed level. The subjects generated 23 ± 7.5 N m and in the pure varus and valgus tasks the soft tissue loading was approximately 20 N m, which is comparable to the 24 N m varus soft tissue loading in walking (this was estimated from the results in Schipplein and Andriacchi, 1991). It is possible that the muscles were activated to provide levels of VV soft tissue loading similar to those experienced in gait. Whether this limit is maintained at higher levels of VV load remains to be seen.

The disadvantage in maximally activating muscles to support VV loads and to protect ligaments is the increase in joint contact forces (Schipplein and Andriacchi, 1991). However, the subjects employed the least effective way of reducing joint contact forces in using co-contraction of the HAMs and QUADs, the muscles with the smallest VV moment arms and thus the greatest muscle forces to provide a level of VV support. In addition, the smallest joint contact forces would result when there is no muscle activity in HAMs and QUADs during the pure varus and pure valgus tasks. So minimization of joint contact forces may be one goal of the nervous system, but not the only one.

Alternatively, the use of HAMs and QUADs co-contraction could just be that this was an appropriate selection from a basic set of activation patterns to provide a level of soft tissue unloading in VV. It is currently believed that there are two basic centrally controlled activation patterns; (1) co-contraction, and (2) reciprocal activation of antagonists (e.g. Humphrey and Reed, 1983). Co-contraction is used to increase joint stiffness for limb positional control in FE (Humphrey and Reed, 1983) and the current results show that this pattern is employed in VV knee stabilization.

It follows that simplicity of the activation pattern used to stabilize the knee may also be the reason for the dominant use of the HAMs and QUADs. Even though the individual HAMs and QUADs have varus or valgus moments arms (Fig. 1B) these muscles were simply activated towards pure flexion and extension respectively (see Fig. 3A in Buchanan and Lloyd, 1997). The overlap HAMs and QUADs activation into pure varus and valgus (Fig. 2) could be interpreted as just a simple stretching of the pure flexion and extension activation patterns in order to stabilize the VV. In addition, the strong reliance on the muscle-joint mechanics to set

the VV moment support is evidence for the use of this simple HAMs and QUADs co-activation strategy.

In summary, HAMs and QUADs co-activation appears to be a main strategy to support VV loads at the knee, with secondary role by the GR and TFL. However, further research is required to identify the goal(s) of the muscle activation strategies used to support VV loads. It will be important to investigate if these VV support strategies identified above are observed in dynamic weight bearing, and to examine the extent to which the gastrocnemi support VV knee moments in these tasks. It will also be essential to see if training or pathology alter the relative contributions of muscles and ligaments to knee joint stabilization.

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