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Sensitivity Analysis of Muscle Parameters and Identification of Effective Muscles in Low Speed Lateral Impact at Just below the Knee

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ABSTRACT

Finite Element simulation of a lower extremity model is used to (1) determine which of the muscle parameters maximum force capacity (F_{max}), initial activation levels (N_a) and maximum muscle contraction velocity (V_{max}) affect ligament strains the most and (2) to identify which muscles affect the knee response the most in low speed, just below the knee, lateral impact. Simulations have been performed with F_{max}, N_a and V_{max} varying from their reference values. Sensitivity of ligament strains to variation in muscle parameters has been studied. It is observed that knee response is more sensitive to F_{max} and N_a than V_{max}. Amongst the muscles varied, reduction in the F_{max} and the N_a in the hamstring and the gastrocnemius muscles affects the knee ligament strains the most. The hamstring parameters significantly affects the ACL, the PCL as well as the MCL strains whereas, change in the gastrocnemius parameters affects only the MCL strain.

INTRODUCTION

In the past, the response of the lower limb, especially the knee joint, in car-pedestrian crashes has been studied using the passive tools such as Post Mortem Human Specimens (PMHS) (Bunketorp et al., 1981; 1983; Aldman et al., 1985; Kajzer et al., 1990; 1993; 1997; 1999; Ramet et al., 1995; Bhalla et al., 2003; 2005; Kerrigan et al., 2003; Bose et al., 2004; Ivarsson et al., 2004; 2005), mechanical surrogates (the EEVC legform by TRL; FlexPLI (Konosu et al., 2005); Polar II pedestrian dummy by Honda R&D; frangible legform by Dunmore et al., 2005) and the passive lower limb FE models (Schuster et al., 2000; Maeno et al., 2001; Takahashi et al., 2001; 2003; Matsui et al., 2001; Nagasaka et al., 2003; Chawla et al., 2004). However, the major shortcoming in existing experimental and computational studies is that they do not account for active muscle forces. In other words, effect of pre-crash muscle contraction on the response of the lower limb in car-pedestrian crashes has not been studied.

Soni et al. (2007) have investigated the effect of muscle contraction using a lower limb (single leg) FE model, A-LEMS, with 42 active muscles. More recently, Chawla et al. (2007) have performed a study using the A-LEMS and reported that with muscle contraction the risk of knee ligament failure is likely to be lower than that predicted through the cadaver tests or simulations with the passive FE models. The values of muscle parameters employed in the A-LEMS are estimates, which have inter and intra subject variability. Therefore, it is essential to investigate how the variation in each muscle parameter affects the knee response during impact loading.

In the present study, we extend our earlier studies to determine which of the muscle parameters, maximum force capacity (F_{max}), initial activation levels (N_a) and maximum muscle contraction velocity (V_{max}) affect the knee response the most and subsequently to identify muscles in the A-LEMS which affect the knee response the most in low speed lateral impact at just below the knee. Since, lower limb muscles share the load with knee ligaments, thus, ligament strains have been

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selected to determine the knee response in the present study. Simulations has been performed after varying the values of F_{max}, N_a and V_{max} from their corresponding reference values and sensitivity of ligament strains to variation in muscle parameters has been studied. In A-LEMS, the reference values of the F_{max} and the N_a have been taken from Delp et al. (1990) and Kuo et al. (1993) respectively. The reference values of the V_{max} have been calculated on the basis of fraction of fast and slow fiber for each muscle, details are given in our earlier study Chawla et al. (2007).

MATERIALS AND METHODS

MODEL GEOMETRY AND VALIDATION STATUS

In the present study, A-LEMS, a lower limb FE model has been used. The A-LEMS includes forty two muscles modeled as 1-D bar elements, in addition to the passive structures such as the cortical and the spongy parts of the femur, tibia, fibula, and the patella. The cortical part of the bones is modeled by shell elements while the spongy part is modeled by solid elements. Apart from these, passive muscle response and skin are also modeled using solid elements and membrane elements respectively. Knee ligaments (see Figure B1 in Appendix B), anterior cruciate ligament (ACL), posterior cruciate ligament (PCL), and lateral collateral ligament (LCL), have been modeled using solid elements. Because of a smaller thickness compared to width, the medial collateral ligament (MCL) has been modeled using the shell elements. The articular capsule i.e. “knee capsule”, which encloses the knee joint and maintains joint integrity, has also been included in this model.

The A-LEMS has been validated against available experimental data. Since all the available data is for cadaver tests, passive version of the A-LEMS was validated for different sets of loading and boundary conditions reported in Kajzer et al. (1997, 1999) and Kerrigan et al. (2003). These validation results have been presented in detail in Soni et al. (2007). The passive model validates for all the test conditions and can correctly reproduce impactor forces, knee kinematics and ligament failures reported from the experiments. After validation, 42 active muscles have been included as 1-D bar elements. Hill material model has then been assigned to each muscle to simulate the effect of muscle contraction. Additional details of muscle modeling are available in Soni et al. (2006 and 2007).

SIMULATION SETUP

In the present study, the A-LEMS has been configured in a standing posture on a rigid ground (Figure 1). The coefficient of friction arising from groves in shoe sole tread and contamination on the road suggests a value of 1.0 (Li K.W. et al. 2006). A concentrated load of 250 N corresponding to half the body weight of AM50 (38.5 kg) minus weight of A-LEMS (13.95 kg) has been applied at the top of femur.

Pedestrian accident studies (Chidester et al. 2001, Mizuno et al. 2005) have shown that risk of bone fracture is higher for high speed impacts. Since, bone fracture unloads the knee joint, the focus in the present study is to load the knee joint without causing bone fracture. Thus, we decided to simulate low speed impact. On the basis of Pedestrian Crash Data Study (PCDS) (Chidester et al. 2001), which reports a range i.e. 20-30 kmph for low speed impacts, an impactor speed of 25 kmph has been selected. Then, impactor mass of 20 kg has been calculated to impart impact energy of 450 J as reported by Matsui et al. (2004). The front surface of the rigid impactor has been covered with equivalent of styrodure© foam (same as in Kajzer et al. 1999). The foam covered rigid impactor contacts the A-LEMS in its lateral side at just below the knee.

Here, muscles in the A-LEMS have been modeled in the “reflex condition” as described in Chawla et al. (2007). Stretch based reflexive action has also been included. Values of the initial activation levels (N_a) and the other muscle parameters (i.e. maximum force capacity (F_{max}) and maximum contraction velocity (V_{max})) used to model the reflex condition are listed in Table A1 in Appendix A. These values have been considered as the reference values and are represented as RN_a, RF_{max} and RV_{max} respectively in the present study. One simulation has been performed using the reference values of the muscle parameters and strain time histories in knee ligaments (ACL, PCL, MCL and LCL) have been extracted. In the present study, these strain time histories have been considered as reference strain time history plots ($R\varepsilon(t)$).

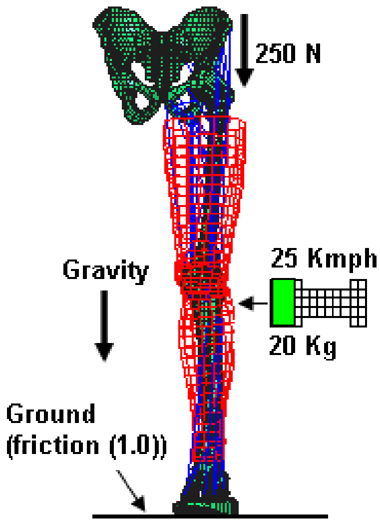

Figure 1 Simulation set up used in the present study

IDENTIFICATION OF EFFECTIVE MUSCLE GROUP(S)

To identify the most effective group(s) of lower extremity muscles, sensitivity of ligament strains to variation in F_{max} has been studied through simulations using A-LEMS. The strain time histories have then been compared with the reference strain time history plots ($R\varepsilon(t)$) to determine the effects of F_{max}.

Since there are 42 muscles in the A-LEMS, thus it would be computationally expensive to perform simulations to study the effects of variation in the F_{max} of every individual muscle. We note that muscles exert force on their attachment points and hence are more likely to affect the joints which they cross. Therefore, in the first step, it has been hypothesized that muscles which cross the knee joint (referred as knee muscles) would be more effective in altering knee loading than other leg muscles (those which do not cross the knee joint, referred as other joints muscles). The 42 lower extremity muscles in A-LEMS have thus been divided into these two major groups (Table 1) i.e. the knee muscles and the other joints muscles. Sensitivity of ligament strains to changes in F_{max} has been investigated for both the muscle groups (i.e. the knee muscles and the other joints muscles). For this, two sets of simulations have been performed. In the first set of simulations, the F_{max} values of only the knee muscles have been reduced by up to 80% (in steps of 20%) of their corresponding RF_{max} values whereas the other joints muscles have been modeled with their RF_{max} values. Similarly, in the second set of simulations, the F_{max} values of only the other joints muscles have been reduced by up to 80% (in steps of 20%) of their corresponding RF_{max} values whereas the knee muscles have been modeled with their RF_{max} values. Effects of this variation in F_{max} on strain time history of knee ligaments have then been studied.

It has been observed in these simulations that the knee muscles are more effective in altering ligament strains than the other joints muscles verifying the hypothesis. In the second step, the knee muscles group has been divided into four subgroups (see Table 1) classified as hamstring, quadriceps, gastrocnemius and GST (Gracilis, Sartorious and Tensor fasciae latae). In the first three subgroups, i.e. the hamstring, the quadriceps and the grastrocnemius, muscles have been grouped on the basis of their functional similarity whereas, in the forth subgroup i.e. the GST, the remaining 3 muscles have been combined. Sensitivity of ligament strains to variation in F_{max} for each subgroup has then been studied. For this, four sets of simulations (corresponding to each subgroup) have been performed. In each set of simulations, the F_{max} values of muscles of only one subgroup have been reduced by up to 80% (in steps of 20%) of their corresponding RF_{max} values whereas all remaining muscles have been modeled with their RF_{max} values. Effects of this variation in F_{max} on strain time history of knee ligaments were then studied.

SENSITIVITY OF LIGAMENT STRAINS TO VARIATION IN INITIAL ACTIVATION LEVELS

The activation level (i.e. N_a) represents the actuation state of a muscle. The central nervous system (CNS) regulates the level of activation in a muscle to perform voluntary and involuntary tasks. Muscle activation level thus changes from minimum (i.e. 0.005) to maximum (i.e. 1) and eventually affects the muscle force generation.

Therefore, sensitivity of ligament strains to variation in the initial activation levels (N_a) of muscles required to maintain standing posture (MSP) has been studied. Here, the MSP (Muscles of the Standing Posture) corresponds to the muscles for which RN_a value is above 0.005 (see Table A1 in Appendix A). Sensitivity of the ligament strains to variation in N_a has been studied in three steps. In the first step, sensitivity to variation in N_a for the MSP (listed in Table 2) has been studied. For this, N_a of the MSP has been reduced by up to 80% (in steps of 20%) of their corresponding RN_a values and simulations have been performed.

Table 1 Classification of 42 lower extremity muscles in A-LEMS

Knee Muscles	Subgroup	Other Joints Muscles
1. Semitendinosus	Hamstring	1. Soleus
2. Semimembranosus	Hamstring	2. Flexor Hallucis & Digit. Longus
3. Biceps Femoris Long head	Hamstring	3. Tibialis Anterior & Posterior
4. Biceps Femoris Short head	Hamstring	4. Extensor Hallucis & Digit. Longus
5. Vastus Lateralis	Quadriceps	5. Peroneus Brevis, Longus & Tertius
6. Vastus Intermedialis	Quadriceps	6. Piriformis
7. Vastus Medialis	Quadriceps	7. Pectineus
8. Rectus Femoris	Quadriceps	8. Obturatorius Internus & Externus
9. Gastrocnemius Medialis	Gastrocnemius	9. Adductor Brevis 1&2
10. Gastrocnemius Lateralis	Gastrocnemius	10. Adductor Longus
11. Gracilis	GST	11. Adductor Mangus 1,2&3
12. Sartorious	GST	12. Gluteus Maximus 1,2&3
13. Tensor Fasciae Latae (TFL)	GST	13. Gluteus Medius 1,2&3
		14. Gluteus Minimus 1,2&3

Table 2 Classification of the muscles of standing posture (MSP)

Knee MSP	Subgroup	Other Joints MSP
1. Semitendinosus	Hamstring	1. Soleus
2. Semimembranosus	Hamstring	2. Tibialis Anterior
3. Biceps femoris Long head	Hamstring	3. Tibialis Posterior
4. Biceps femoris Short head	Hamstring	4. Peroneus Brevis
5. Gastrocnemius Medialis	Gastrocnemius	5. Adductor Longus
6. Gastrocnemius Lateralis	Gastrocnemius	6. Gluteus Maximus 1
7. Tensor Fasciae Latae	TFL	7. Gluteus Maximus 2
		8. Gluteus Maximus 3

In these simulations, strains in knee ligaments have been calculated and then compared to investigate the effects of N_a.

Subsequently, in the second step, 15 muscles of the standing posture (MSP) have been divided into two major groups (Table 2) named as knee MSP (7 muscles) and other joints MSP (8 muscles). Then, sensitivity to variation in N_a for these muscle groups (i.e. the knee MSP and the other joints MSP) has been studied in a similar manner. Then, in the third step, muscles of the knee MSP have been further divided into three subgroups (Table 2) named as hamstring, gastrocnemius and tensor fasciae latae (TFL). Sensitivity to variation in N_a for each subgroup has then been studied.

SENSITIVITY OF LIGAMENT STRAINS TO VARIATION IN MAXIMUM CONTRACTION VELOCITY

The maximum muscle contraction velocity (i.e. V_{max}) characterizes the force-velocity (F-V) relationship of an activated muscle. The F-V relationship explains that the faster a muscle contract (which also means the faster movement of a limb) the lesser it generates the force. If a muscle contracts with a speed of V_{max} or above, it generates zero force. Since, the V_{max} directly affects the muscle force generation, it is important to investigate sensitivity of ligament strains to variation in V_{max} during the impact loading.

Further, V_{max} is a function of fraction of fast or slow types of fibers in a muscle. The fraction is known for muscle types. A muscle with larger fraction of fast fibers generates smaller force in static conditions but produces force till higher contraction speeds. Literature on sports biomechanics has suggested that a muscle can be trained to become faster such as in sprint runners, however, no evidence of contrary (i.e. conversion of fast muscles into slow muscles) has been reported. In view of this, the V_{max} of the 42 muscles in the A-LEMS has been increased by up to 50% (in steps of 10%) from their corresponding RVmax values and simulations have been performed. Ligament strain time histories have been calculated in these simulations and compared with the reference strain time history plots. Since no significant deviation in the ligament strains has been observed in these simulations, sensitivity to variation in Vmax for individual muscles has not been studied further.

DATA ANALYSIS

In the present study, simulations have been performed to investigate the sensitivity of ligament strains to variation in muscle parameters i.e. F_{max}, N_a and V_{max}. In these simulations, change in ligament strain time history plots (ε(t)) has been calculated. To eliminate any subjective prejudices in the comparison, root mean square deviation (RMSD) between ε(t) and Rε(t) has been calculated (Equation (1)). The calculated RMSD values have then been compared to determine the sensitivity of ligament strains to variation in the muscle parameters.

$$RMSD_j = \sqrt{\frac{\sum_{i=1}^{N} (\varepsilon_j(t_i) - R\varepsilon_j(t_i))^2}{N}}$$

(1)

Where, j = ACL, PCL, MCL or LCL and N is the number of data points.

Time history plots have been recorded at a sampling rate of 10 kHz. As a result, for a simulation of 50 ms duration, 500 data points have been obtained in each strain time history plot.

RESULTS AND DISCUSSIONS

EFFECTIVE MUSCLE GROUP(S)

The variation in root mean square deviation (RMSD) in strain in knee ligaments (ACL, PCL, MCL, and LCL) to percentage reduction in the maximum force capacity (F_{max}) of different groups of muscles has been shown in Figure 2.

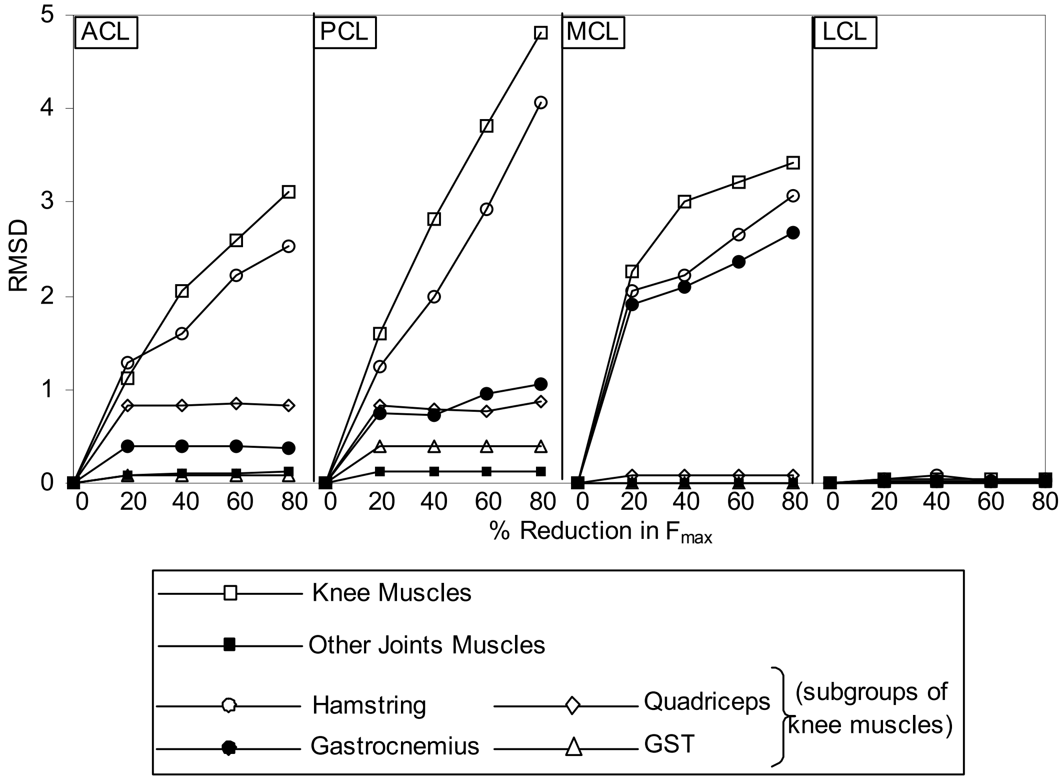

Figure 2 Sensitivity of ligament strains to variation in maximum muscle force

It is evident from Figure 2 that strains in all the knee ligaments, except the LCL, are sensitive to the variation in the F_{max}. It can be seen (Figure 2) that, for the knee muscles, RMSD values are higher (maximum RMSD values 3.11, 4.8 and 3.41 in the ACL, the PCL and the MCL respectively at 80% reduction) than for the other joints muscles (RMSD values nearly zero for all the ligaments). This confirms the hypothesis of the first step that the knee muscles are more effective in altering ligament strains than the other joints muscles.

RMSD values for individual subgroups of the knee muscles (i.e. hamstring, gastrocnemius, quadriceps and GST) have also been compared in Figure 2. It is found that, in the ACL and the PCL, the RMSD values are higher for the hamstring (maximum RMSD values 2.5 and 4.07 in ACL and PCL respectively at 80% reduction) than the other subgroups (RMSD values are less than 1.0). Whereas, in the MCL (Figure 2), the RMSD values are higher for the hamstring (maximum RMSD value 3.07 at 80% reduction) and the gastrocnemius (maximum RMSD value 2.67 at 80% reduction) than the quadriceps and the GST (RMSD values are nearly zero). This indicates that strains in the ACL and the PCL are sensitive to maximum force capacity of the hamstring, whereas, strain in the MCL is sensitive to maximum force capacity of the hamstring and the gastrocnemius.

Figure 3 shows the comparison between the reference ligament strain time histories and the strain time histories calculated in the simulation performed with 80% reduced F_{max} values of the hamstring. It shows that due to reduction in the F_{max} values of the hamstring, strains in the ACL and the PCL (Figure 3) are increased as compared to their reference strain values.

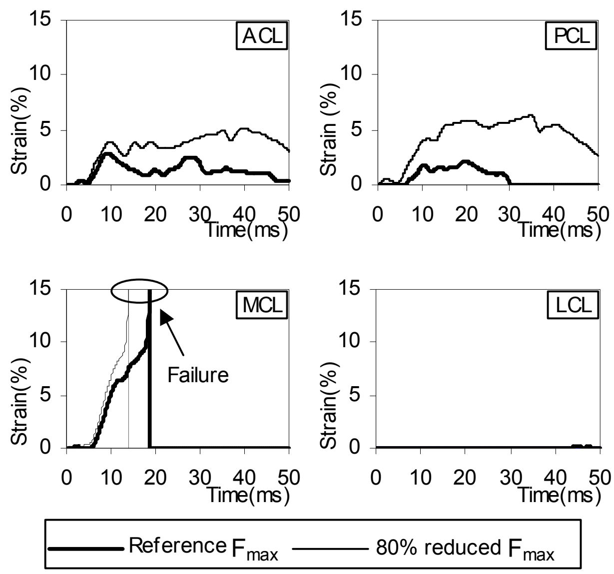

Figure 3 Comparison of the reference ligament strains with that calculated in the simulation performed with 80% reduced Fmax values of the hamstring

It has been observed that the MCL has failed in both the simulations; however, failure occurrence time has reduced by approximately 5 ms (Figure 3) in the simulation with 80% reduced F_{max} values of the hamstring. It is seen that the LCL has remained almost unstrained for the entire duration in both the simulations. This can be attributed to the lateral impact. This also explains the reason of zero RMSD values in the LCL (in Figure 2) for all the simulations.

INITIAL ACTIVATION LEVELS

The variation in root mean square deviation (RMSD) in strain in knee ligaments (ACL, PCL, MCL, and LCL) to variation in percentage reduction in the initial activation levels (N_a) of the groups and subgroups of the muscles of standing posture (MSP) has been shown in Figure 4. It is evident from Figure 4 that strains in all the knee ligaments, except the LCL, are sensitive to the variation in the N_a of the MSP. Higher values of RMSD are observed in the PCL (4.34 at 80% reduction) than the ACL (2.39 at 80% reduction) and the MCL (3.36 at 80% reduction).

RMSD values for the major groups of the MSP (i.e. the knee MSP and the other joints MSP) have been compared. It can be seen in Figure 4 that, for the knee MSP, the RMSD values are higher (maximum RMSD values 3.27, 5.0 and 3.44 in ACL, PCL and the MCL respectively at 80% reduction) than for the other joints MSP (RMSD values are below 1.0 for the ACL, PCL and the MCL). This indicates that ligament strains are more sensitive to the initial activation levels of the knee MSP that the other joints MSP.

RMSD values for subgroups of the knee MSP (i.e. the hamstring, the gastrocnemius and the TFL) have also been compared in Figure 4. It is found that, in the ACL and the PCL, the RMSD values are higher for the hamstring (maximum RMSD values 2.83 and 4.0 in ACL and PCL respectively at 80% reduction) than the other subgroups (RMSD values are less than 1.0). Whereas, in the MCL (Figure 4), the RMSD values are higher for the hamstring (maximum RMSD value 3.14 at 80% reduction) and the gastrocnemius (maximum RMSD value 2.68 at 80% reduction) than the TFL (RMSD values are nearly zero). This indicates that strains in the ACL and the PCL are sensitive to initial activation level in the hamstring, whereas, strain in the MCL is sensitive to initial activation level in the hamstring and the gastrocnemius.

MAXIMUM CONTRACTION VELOCITY

The variation in root mean square deviation (RMSD) in percentage strain in knee ligaments (ACL, PCL, MCL, and LCL) to variation in percentage increase in the maximum contraction velocity (V_{max}) of all 42 muscles in the A-LEMS has been shown in Figure 5.

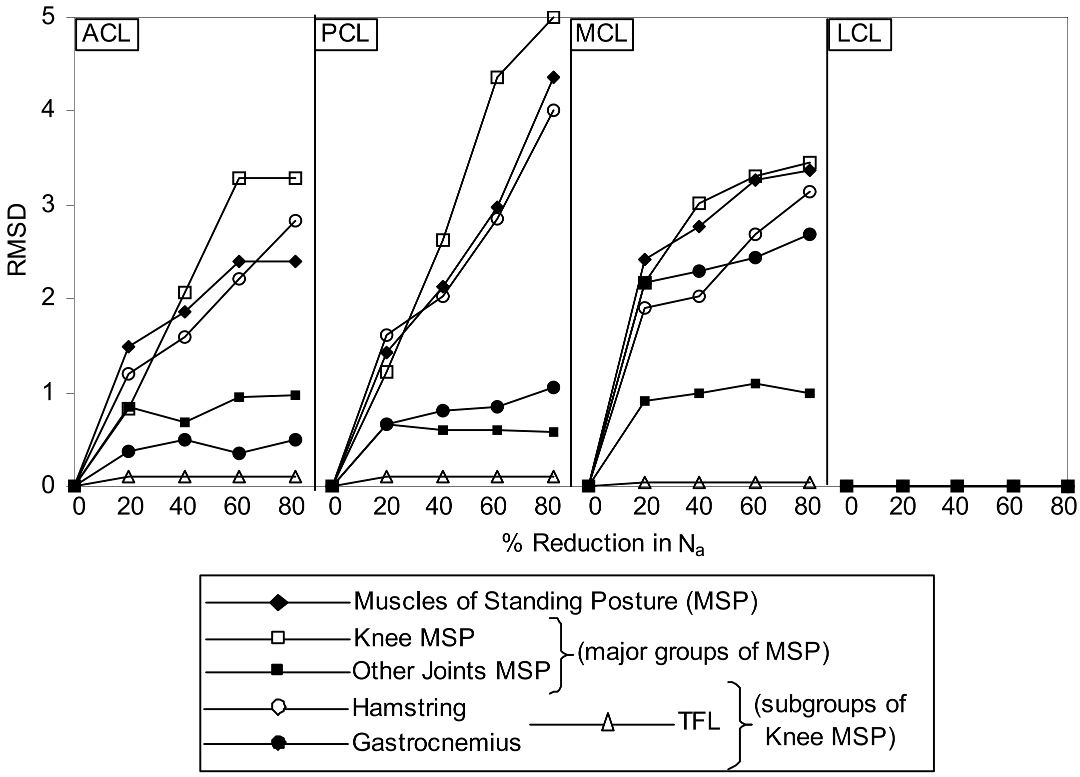

Figure 4 Sensitivity of ligament strains to variation in initial activation levels

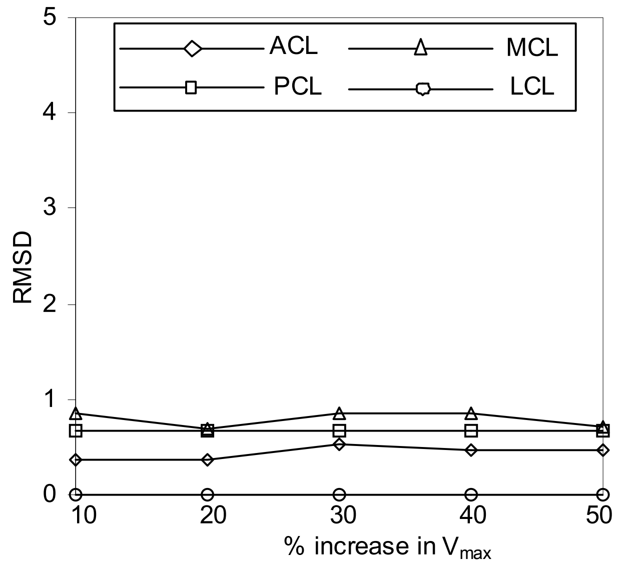

Figure 5 Sensitivity of ligament strains to variation in maximum contraction velocity

It has been observed that, the RMSD values for all four knee ligaments remain below 1.0. This indicates that maximum contraction velocity of the muscles do not affect ligament strains. This could be because muscles in the A-LEMS have been modeled for static standing posture.

CONCLUSIONS

In the present study, sensitivity of ligament strains to variation in the muscle parameters maximum force capacity (F_{max}), initial activation levels (N_a) and maximum muscle contraction velocity (V_{max}) in low sped lateral impact at just below the knee has been studied. Subsequently, muscles in the A-LEMS, which are more effective in altering the knee loading in low speed lateral impact at just below the knee location have been identified. In all, 54 simulations have been performed in the present study. Following conclusions can be drawn.

1. Ligament strains are more sensitive to the maximum force capacity (F_{max}) and the initial activation levels (N_a) than the maximum contraction velocity (V_{max}).
2. Reduction in the Fmax and the Na in the hamstring and the gastrocnemius muscles affects knee ligament strains the most.
3. The hamstring affects strain in the ACL, the PCL and the MCL whereas; the gastrocnemius affects only the MCL strain.

LIMITATIONS

A lower limb muscle, which has moment arm about the knee joint in lateral-medial (L-M) bending, would directly affect the L-M response of the knee joint. Llyod et al. (2001) have shown that both the hamstring and the gastrocnemius muscles have L-M moment arm. This indicates that these muscles can modify the knee response in L-M loading. In the present study, we have observed that the hamstring and the gastrocnemius muscles have relatively higher effects on the knee response in lateral impact. However, it is important to note here that muscles of both the groups have complex 3-dimensional geometry, especially around the knee joint. The exact way of representing line of action of these muscles about the knee joint would be to describe their three-dimensional centroidal path on bones. However, the detailed description of a muscle's centroidal path is complex. Therefore, in A-LEMS, we have adopted a straight line geometric modeling approach due to its simplicity of definition using the origin and insertion locations of these muscles. It is likely that this approach may lead to erroneous results due to wrong estimation of moment arm and the torque produced by these muscles about the knee joint. The results of this study are thus subjected to limitations due to muscle modeling and need further improvements.

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APPENDIX - A

Table A1 Reference values of the muscle parameters. [RF_{max} and (*) RN_a have been taken from Delp et al. (1990) and Kuo et al. (1993) respectively. RaV_{max} for each muscle are as reported in Chawla et al. (2007).]

Lower extremity muscles	RF_{max} (N)	RaV_{max}	RN_a
Vastus Lateralis	1871	5.85	0.005
Vastus Intermedius	1365	5.10	0.005
Vastus Medialis	1294	5.36	0.005
Rectus Femoris	779	5.55	0.005
Soleus	2839	2.67	1.0*
Gastrocnemius Medialis	1113	5.74	1.0*
Gastrocnemius Lateralis	488	5.69	1.0*
Flexor Hallucis Longus	322	5.17	0.005
Flexor Digitorium Longus	310	4.58	0.005
Tibialis Posterior	1270	4.65	1.0*
Tibialis Anterior	603	3.28	0.5*
Extensor Digitorium Longus	341	5.31	0.005
Extensor Hallucis Longus	108	4.32	0.005
Peroneus Brevis	348	4.59	1.0*
Peroneus longus	754	4.35	0.005
Peroneus Tertius	90	4.76	0.005
Biceps Femoris (LH)	717	3.55	1.0*
Biceps Femoris (SH)	402	3.91	1.0*
Semimembranosus	1030	5.61	1.0*
Semitendinosus	328	4.76	1.0*
Piriformis	296	5.71	0.005
Pectineus	177	4.62	0.005
Obturatorius Internus	254	5.71	0.005
Obturatorius Externus	109	5.71	0.005
Gracilis	108	5.13	0.005
Adductor Brevis 1	286	5.17	0.005
Adductor brevis 2	286	5.22	0.005
Adductor Longus	418	4.69	0.5*
Adductor Mangus 1	346	5.07	0.005
Adductor Mangus 2	444	5.07	0.005
Adductor Mangus 3	155	5.07	0.005
Gluteus Maximus 1	382	5.53	0.005
Gluteus Maximus 2	546	5.53	0.005
Gluteus Maximus 3	368	5.53	0.005
Gluteus Medius 1	546	5.71	0.005
Gluteus Medius 2	382	5.71	0.005
Gluteus Medius 3	435	5.71	0.005
Gluteus Minimus 1	180	5.71	0.005
Gluteus Minimus 2	190	5.71	0.005

Gluteus Minimus 3	215	5.71	0.005
Sartorius	104	5.03	0.005
Tensor Fasciae Latae	155	5.71	1.0*

APPENDIX - B

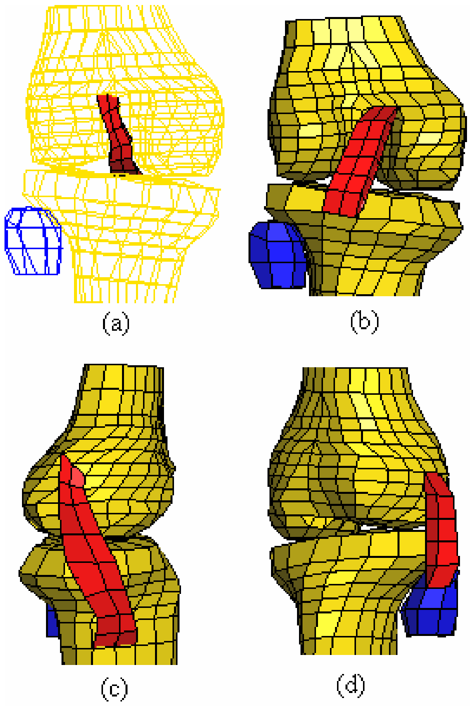

Figure B1 The knee ligaments modeled in the A-LEMS (a) ACL, (b) PCL, (c) MCL and (d) LCL