# Reflex responses to ligament loading: Implications for knee joint stability

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*Abstract-* **To assess the neuromuscular reflex responses to loading of knee ligaments, we applied an abducting positional deflection to the fully extended knee using a servomotor, and recorded EMG activity in pre-activated quadriceps and hamstrings muscles with surface electrodes. To establish that the reflex response elicited by the perturbation was not simply a form of muscle stretch response, a tendon tap was applied to the muscles at the same setting and the reflex responses recorded from the same subject. Contrary to the typical muscle stretch reflex, which is of short duration and has a short latency (28-35msecs for knee muscles), the abduction response was characterized by long latency responses with an initial EMG peak followed by sustained muscle activity throughout the duration of the step perturbation. The latency of the abduction response was at least twice the latency of the tap reflex suggesting a different (possibly ligamentous) origin (60-85msecs for knee muscles). This reflex was consistent throughout the set of trials performed at the same speed and amplitude of perturbation. Our investigation showed that the sustained activity of the abduction reflex is dependent on the amplitude of the perturbing stimulus. Furthermore, the knee muscle contractions elicited were sometimes selective, depending on the magnitude of the angular perturbation.**

*Keywords* - **Reflex, Periarticular tissue afferents, Joint stability**

## I. INTRODUCTION

Traditionally, joint stability has been considered to be purely mechanical in origin, with little or no consideration of neuromuscular involvement. It has been long assumed that the role of joint passive tissues, such as ligaments, is to provide mechanical constraints to joint movement. Such a role has been challenged by clinical observations. For example, patients can have a torn anterior cruciate ligament without evidence of anterior/posterior joint instability. This suggests that there may be other *nonstructural* roles for periarticular tissues in promoting joint stability. Based on early studies in animal models, such a role is potentially *neurosensory* in origin.

The human knee is surrounded by connective tissues that contain multiple nerve endings [1-3]. Similar nerve endings have also been found in the periarticular tissues around the cat knee joint [4-6]. Several studies have shown significant increases in afferent discharge in the medial and posterior articular nerves in cats in response to static mechanical stimuli applied at the joint's capsule or ligaments [7,8]. Thus, knee joint mechanoreceptors may promote stability by providing sensory feedback, which allows selective activation of muscles around the knee [9-12].

Accordingly, our goal is to investigate, in vivo, the reflex actions of the periarticular afferents at the human knee. We hypothesize that such reflexes can be elicited by the application of a mechanical abduction stimulus to the human knee. We further hypothesize that these contractions may be selective in promoting joint stability by reducing ligament strain.

## II. METHODS

### 1) *Experimental Protocol*

We applied an abducting knee positional deflection at random to the fully extended knee using a servomotor, and recorded EMG activity in the pre-activated rectus femoris (RF), vastus lateralis (VL), vastus medialis oblique (VMO) and longus (VML), semitendinosus (ST) and biceps femoris (BS) muscles with pre-amplified surface electrodes (*Delsys Inc.*). Subjects were seated in a chair, with the trunk supported under the ischial tuberosities. A cast was placed around the ankle joint. The leg was then placed within a coupling ring, which was then fixed to a servomotor actuator and to a precision potentiometer and tachometer mounted on the actuator. The actuator support included hardware safety stops, essential for subject's safety. The knee was fitted with a bracket mounted firmly at the medial and lateral femoral epicondyles. The brackets were used to isolate the knee adduction-abduction movement from the abduction/adduction movement of the hip joint. Prior to each perturbation sequence, subjects were asked to maintain a steady low-level co-contraction of the hamstrings and quadriceps during an on going abduction perturbation (~15% of MVC). A visual display was provided for subject feedback. Maximum voluntary EMG levels were recorded for the subject at a knee flexion angle of $60^{\circ}$ (less than full extension). At the same angle, the EMG response to tendon tap was recorded using a tapper with a mounted load cell (*Kistler Instrument Corp.*) to identify the onset of the tendon tap.

### 2) *Data Analysis*

To determine the timing and intensity of the reflex activity, the EMG response was subdivided in to two components; a dynamic response (DR) and a sustained response (SR). The DR activity occurred in the first 40 msecs from the onset of the ramp position perturbation to the time corresponding to the end of the ramp stimulus, $t_2$. The SR was the EMG activity during a sustained abduction position stimulus at the knee that lasted for 1200 msecs (the time window between $t_2$ and $t_3$; see Fig. 1). Fig. 1 shows both the position stimulus signal and a representative EMG activity with both components of the response represented.

To estimate the onset latency of the DR elicited by the abducting perturbation, the EMG signal was rectified and smoothed and an ensemble average was taken across all identical trials. A baseline EMG signal and the corresponding standard deviation were calculated 100 msecs prior to the onset of the mechanical stimulus, $t_o$. A window of 40 to 120 msecs after the onset of the mechanical stimulus was used to search for the onset of the reflex burst, $t_1$. A burst was identified when five consecutive points in the EMG trace were above three standard deviations of the pre stimulus EMG activity.

To establish that the reflex response (shown in Fig. 1) elicited was not simply a form of tendon tap response

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**Abstract**

**Subject Terms**

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mediated by the "percussive" effect of the perturbation, tendon taps were applied to the patellar tendon and the resulting reflex response was recorded. A minimum of 15 repeated taps were delivered to the patellar tendon of each subject over a period of 25 sec. The signals collected were then filtered with an $8^{th}$ order Butterworth filter at 220 Hz cut-off frequency. Tap response latencies were then calculated for the same subject at the same setting, and for same EMG electrode locations. The latencies computed using a threshold criterion similar to the Zhang et al. [13].

The consistency of the sustained response was tested by cross-correlating the SR response of a minimum of five trials obtained at the same angular perturbation applied at the same speed. Sustained reflex responses across different trials for each muscle at each angular perturbation were cross-correlated via a waveform alignment algorithm [14]. Cross correlation is a standard method of estimating the degree to which two series are correlated. Consider two sustained reflex series $x(i)$ and $y(i)$, where $i = 0,1,2...N\text{-}1$. The cross correlation $r$ at lag $k$ is defined as

$$r(k) = \frac{\sum_i (x(i)-\bar{x})\cdot(y(i)-\bar{y})}{\sqrt{\sum_i (x(i)-\bar{x})^2}\cdot\sqrt{\sum_i (y(i)-\bar{y})^2}} \qquad (1)$$

where $\bar{x}$ and $\bar{y}$ are the means of the corresponding series. If the above is computed for all lags $k = 0,1,2,...N\text{-}1$ then it results in a cross correlation series of twice the length as the original series. A consistent sustained response, will be represented with intra-trial cross-correlation of maximum value close to one located at zero lag.

To quantify the intensity of the sustained as well as the dynamic activity, a normalized reflex activity (NR) measure was used for all muscles as follows

$$NR = \frac{EMG_{rms}^{reflex} - EMG_{rms}^{baseline}}{EMG_{rms}^{MVC} - EMG_{rms}^{baseline}} \qquad (2)$$

where $EMG_{rms}^{reflex}$ is the time average of the EMG activity during the reflex activity period (from $t_1$ to $t_2$ for DR and from $t_2$ to $t_3$ for the SR), $EMG_{rms}^{baseline}$ is the time average of the baseline activity calculated over 100msecs before the onset of the mechanical perturbation, and $EMG_{rms}^{MVC}$ is the time average of the EMG activity recorded over 100msecs at maximum MVC in flexion or extension. From this normalization process (2), all muscles supporting the hypothesis would have ratios greater than zero at a given adduction or abduction angular perturbation. That is, a reflex activity can be elicited via adduction or abduction mechanical perturbation at the knee joint. This measure, a single value was used for all the subjects included in this study. Student's *t*-test ($P < .01$) was used to determine if the normalized reflex activity is significantly greater than zero.

## III. Results

### A. Nature of The Reflex Response

The data shown in Fig. 1 represents the abduction-induced reflex response of RF for a representative subject. The figure shows the two main components of the reflex; the dynamic and the sustained responses. Also shown in Fig. 1 are the latencies of the tendon tap reflex and the perturbation-induced reflex (see the table in the figure). The data shown indicate that the latency of the abduction response was at least twice the latency of the tap reflex suggesting a different (possibly ligamentous) origin.

### B. Consistency of the sustained reflex response

As shown in Fig. 2, intra-trial cross-correlations are highly significant (>95%), with maximum at zero lag. Thus, it is highly unlikely that the sustained responses are due to other sources, such as the subject's voluntary contraction.

### C. Quantification of the reflex muscle contractions elicited via the angular joint perturbation

The sustained NR in RF was recorded in four subjects as a function of the abduction angular perturbation. These subjects had no history of neurological and musculoskeletal disorders. The data shown in Fig. 3 was obtained with perturbation speed of $60^{o/s}$. Student's t-test ($p < 0.01$) was used to determine if the normalized reflex activity is significantly greater than zero at a specific angle for each subject. All responses were statistically significant. Repeated measures analysis of variance revealed a significant effect of angle, subject, and angle x subject ($p < 0.001$) on the normalized sustained reflex.

To quantify the input (abduction angle)/output (NR) properties of the sustained response, an exponential regression model was used given as

$$NR = A \cdot e^{B\theta} \qquad (3)$$

where $\theta$ is the abduction angle and $A$ and $B$ are constants. The corresponding values as well the statistical significance

| | Tendon Tap Reflex Onset Latency (msec) | Dynamic Response Onset Latancy (msec) |
|---|---|---|
| RF | 28 +/- 1.7 | 70 |
| VL | 31 +/- 1 | 71 |
| VMO | 28.3 +/- 0.6 | 82 |

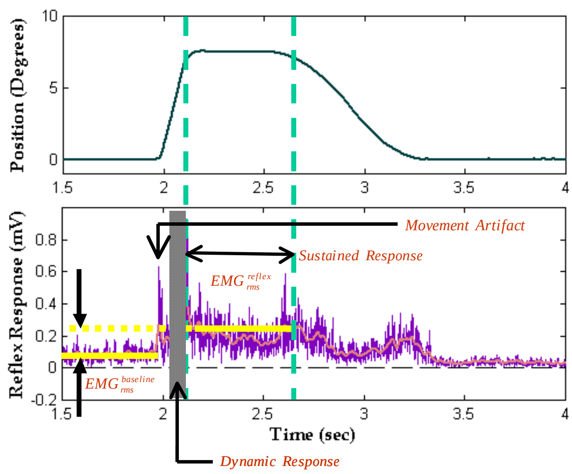


Fig. 1. Position and EMG activity of the RF muscle associated with abduction perturbation for a representative subject. The starting angle was set at 4 degrees knee abduction angle. The table shows the reflex onsets in milliseconds for the same subject at the same setting for both the tendon tap and mechanical perturbation experiments for three muscles.

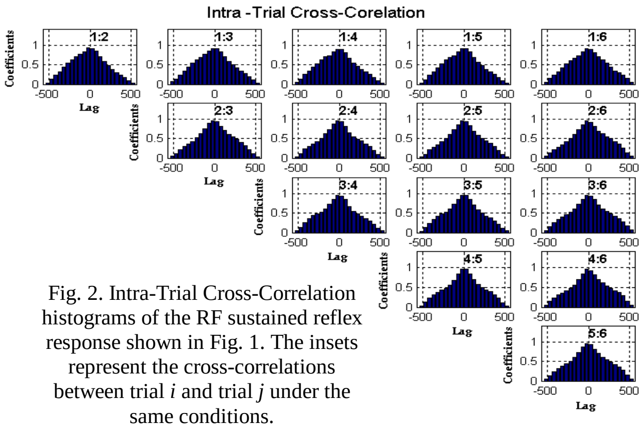


Fig. 2. Intra-Trial Cross-Correlation histograms of the RF sustained reflex response shown in Fig. 1. The insets represent the cross-correlations between trial *i* and trial *j* under the same conditions.

of the constant are shown in the table of Fig. 3. The regression model coefficients were significant for all subjects while the exponential model was a good predictor of the relationship between the NR and the angle in three of the four subjects shown.

Since the reflex activity is shown to increase broadly with increasing knee abduction angle (see Fig. 3 and the significance of the regression model), which presumably results in an increase of the strain in knee ligament tissues, such an increase would follow the exponential stress/strain relation in ligamentous tissues.

*D. Distribution of the perturbation-induced reflex among medial and lateral knee joint muscles*

To investigate grouping of muscle activity in the quadriceps and hamstrings in response to angular abduction perturbation, the normalized sustained response was quantified (using (2) in Data Analysis) for RF, VL, VMO, VML, ST and BS. A two way ANOVA of the data shown in Fig. 4 indicates that the reflex activity is muscle dependent, and varies as a function of angle.

A post hoc analysis of the data revealed that all muscles displayed sustained NR in response to a 5, 10 and 12 degrees perturbation, respectively (Table I). In the table, the means of the sustained NR are listed in an ascending order. There is substantial reflex activity of the VMO (a medial muscle) and a low level activity in the BS (a lateral muscle) in response to a lateral perturbation when compared to the activity of the other muscles.

| **Subjects** | **A** | **B** | **$R^2$** |
|---|---|---|---|
| **S1** | **0.0345** | **0.089** | **0.637** |
| **S2** | **0.0854** | **0.084** | **0.814** |
| **S3** | **0.0388** | **0.052** | **0.661** |
| **S4** | **0.0422** | **0.037** | **0.376** |

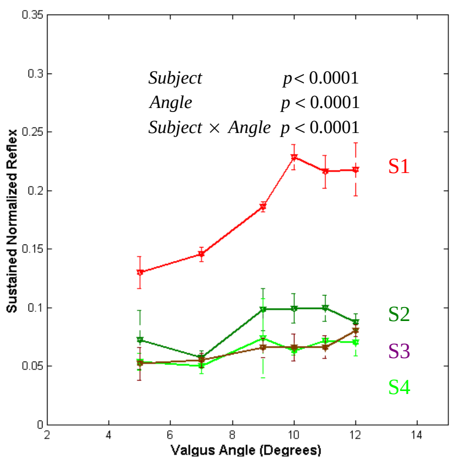


Fig. 3. The sustained normalized reflex response of the rectus femoris as a function of the abduction perturbation for four subjects, S1, S2, S3, and S4. Data is displayed as means and ±SD. The table provides a list of the regression coefficients and the corresponding statistical measures.

IV. DISCUSSION

Our results show that reflex activity is evoked systematically in a number of major knee muscles by abducting angular positional perturbations of the knee. In contrast to the typical stretch reflex, the perturbation-induced reflex is characterized by a longer latency response with an initial peak followed by a sustained muscle activity throughout the duration of the step perturbation. The late onset of the reflex implies that joint mechanoreceptors operate through polysynaptic pathways, as has been suggested by Freeman and Wyke [15].

Morphological examination of ligament afferents indicates that free nerve endings are the most common type of nerve endings present [2]. Ultrastructurally, the terminal of the free nerve ending is pierced by connective tissue (collagen) in the joint capsule [16-18]. Deformation of the collagen fiber through loading of the tissue provides the mechanical stimuli necessary for the discharge of these nerve endings [18]. Using neurons from cat knee joint capsule, Grigg and Hoffman [19] showed a linear relation between the neural discharge rate and the tension applied to the ligament. Experimental [20] as well as analytical [21] investigations showed that tissue deformation (strain) increases exponentially with the magnitude of the applied tension.

On the basis of these findings and the observed nonlinear trend between reflex activity and the magnitude of abduction perturbation, we believe that slow adapting fibers (probably free nerve endings) in the joint's ligaments were responsible for the sustained response.

Furthermore, the data in Table I suggest that two motor control strategies are elicited in response to the ligament

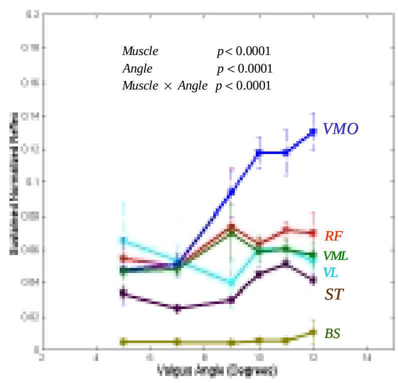


Fig. 4. The sustained normalized reflex of knee muscles for a representative subject as a function of the abduction perturbation.

TABLE I

Muscle grouping of the data given in Fig. 4 based on a post hoc pairwise analysis of variance with $p < 0.001$. The six muscles are ranked by mean normalized percentile reflex for three angular perturbations.

| | MUSCLES | *Mean NR* | Groups | | | | |
|---|---|---|---|---|---|---|---|
| | *BS* | 0.47 | 1 | | | | |
| | *ST* | 3.38 | | 2 | | | |
| *5 Degrees* | *VML* | 4.63 | | 2 | 3 | | |
| | *VMO* | 4.75 | | 2 | 3 | | |
| | *RF* | 5.42 | | 2 | 3 | | |
| | *VL* | 6.55 | | | 3 | | |
| | *BS* | 0.537 | 1 | | | | |
| | *ST* | 4.48 | | 2 | | | |
| *10 Degrees* | *VML* | 5.86 | | | 3 | | |
| | *VL* | 6 | | | 3 | | |
| | *RF* | 6.36 | | | 3 | | |
| | *VMO* | 11.77 | | | | 4 | |
| | *BS* | 1.08 | 1 | | | | |
| | *ST* | 4.14 | | 2 | | | |
| *12 Degrees* | *VL* | 5.32 | | 2 | 3 | | |
| | *VML* | 5.68 | | | 3 | 4 | |
| | *RF* | 7.02 | | | | 4 | |
| | *VMO* | 13.07 | | | | | 5 |

stimulus: (a) uniform activity at low level perturbations directed to increase the joint stiffness through co-contraction [22], and (b) selective activation based on the efficient biomechanical role of muscles.

In the context of our preliminary data, the latter strategy is shown by the substantial reflex activity of the vastus medialis oblique (a medial muscle) and the low-level activity in the biceps femoris (a lateral muscle) in response to a lateral perturbation.

## V. Conclusion

These early results support an important role for ligamentous afferents in providing an additional layer of control that could minimize the destabilizing effect of externally applied abducting/adducting joint loads to the knee.

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