Effects of Series Elasticity of the Muscle Tendon Complex on an Explosive Activity Performance With a Counter Movement

Akinori Nagano1,4, Taku Komura2, and Senshi Fukashiro3

1Boston University; 2City University of Hong Kong; 3University of Tokyo; 4RIKEN, Japan

The two goals of this study were (a) to evaluate the effects of the series elasticity of the muscle tendon complex on an explosive performance that allows a counter movement, and (b) to determine whether or not a counter movement is automatically generated in the optimal explosive activity, using computer simulation. A computer simulation model of the Hill-type muscle tendon complex, which is composed of a contractile element (CE) and a series elastic element (SEE), was constructed. The proximal end of the CE was affixed to a point in the gravitational field, and a massless supporting object was affixed to the distal end of the SEE. An inertia was held on the supporting object. The goal of the explosive activity was to maximize the height reached by the inertia. A variation of the SEE elasticity was examined within the natural range. The optimal pattern of neural activation input was sought through numerical optimization for each value of the SEE elasticity. Two major findings were obtained: (a) As the SEE elasticity increased, the maximal height reached by the inertia increased. This was primarily due to the enhanced force development of the CE. (b) A counter movement was automatically generated for all values of the SEE elasticity through the numerical optimization. It is suggested that it is beneficial to make a counter movement in order to reach a greater jump height, and the effect of making a counter movement increases as the elasticity of the muscle tendon complex increases.

Key Words: compliance, jumping, computer simulation

It is widely recognized that the elasticity of the musculoskeletal system plays an important role in generating explosive muscular activities (Bosco, Komi, & Ito, 2004).

Nagano, Komura, and Fukashiro (1981; Cavagna, 1977; Hoy, Zajac, & Gordon, 1990; Komi & Bosco, 1978). Kubo et al. (Kubo, Kawakami, & Fukunaga, 1999) examined the influence of muscle tendon elasticity on jumping performance in humans. Squat jumping (SQJ) and counter-movement jumping (CMJ) motions were recorded and analyzed. In addition, in order to determine the elasticity of the tendinous structures, Kubo et al., (1999) studied the behavior of the tendon and aponeurosis of the m. vastus lateralis using ultrasonography while the participants performed ramp isometric knee extension exercises. The relationship between the elasticity of the tendinous structures and jumping performance was discussed. There was a tendency for the more elastic tendinous structures to be related to better jump performance. It was concluded that the elasticity of the tendinous structures has a favorable effect on the stretch-shortening cycle exercise.

Bobbert (2001) looked at the effects of the series elasticity of the mm. triceps surae on human squat jumping (SQJ) performance in a computer simulation study. Counter movement jumping was not investigated. In that study the elasticity of the series elastic element (SEE) was modified systematically. It was found that jumping performance was the highest when the SEE elasticity was the highest. It should be noted that as SQJ was simulated in Bobbert (2001), the model did not allow a counter movement. Considering the fact that typically higher jumping performance is observed in CMJ than in SQJ, it is beneficial to examine the behavior of the muscle tendon complex in explosive activities that allow counter movements, with a special emphasis on the contribution of series elasticity. Therefore, the first purpose of this study was to examine the effects of the SEE elasticity on an explosive muscular activity that allows a counter movement.

In a study by Bobbert, Gerritsen, Litjens, and van Soest (1996), two types of jumping motions were examined and compared using computer simulation: SQJ and CMJ. In that study the computer simulation model was set to perform two types of jumping. However, in normal activities humans first define the goal of a motion (e.g., to reach as high as possible), implicitly select the best strategy (e.g., CMJ), and perform the most suitable motion in the optimal way. From this perspective, in computer modeling and simulation studies, it would be more realistic to “tell” the computer model only the ultimate goal to be accomplished and then let the optimization process choose the best strategy. Therefore, the second goal of this study was to determine, through computer simulation and numerical optimization, whether or not a counter movement is automatically generated in explosive muscular activity.

To accomplish these goals, the use of a complex (i.e., multiple segments and multiple muscles; Nagano & Gerritsen, 2001) computer simulation model of the neuromusculoskeletal system is problematic. It is computationally very demanding to use a complex model and let the optimization process choose whether or not to make a counter movement. Instead, many researchers have undertaken independent studies for SQJ and CMJ, even when using the identical model. Therefore, in typical cases it was necessary to run independent procedures for SQJ and CMJ and then compare the results. The current study utilized a simple model consisting of a muscle tendon complex and an inertia. With this simple model it was possible to define only the ultimate goal and let the optimization process choose the best strategy to take.
A Hill-type (Hill, 1938) muscle tendon complex model was developed for this computer simulation study. The model consisted of two elements, a contractile element (CE) representing muscle fibers and a series elastic element (SEE) representing all series elasticity. The proximal end of the CE was affixed to a point in the gravitational field (Figure 1). A massless supporting object was affixed to the distal end of the SEE. An inertia was held on the supporting object (Figure 1). Mechanically, an explosive lifting of this inertia through the contraction of the muscle tendon complex model corresponds to jumping. All model development procedures were conducted using MATLAB (MathWorks, Natick, MA).

The CE model represented the force-length and force-velocity relationships reported by Hill (1938). The range of isometric force development capability of the CE was defined as 45–155% of the optimal contractile element length (Allinger, Herzog, & Epstein, 1996). Force development characteristic of the SEE was modeled as a quadratic function of the strain of the SEE. In a normal SEE the strain is approximately 4% (Caldwell, 1995) when the loaded force is equal to $F_{\text{MAX}}$, i.e., the maximal isometric CE force.

Seven values of the SEE elasticity, from 1% (stiff) to 7% (elastic), were examined in this study. The range of 1% to 7% covers the variation in tendon elasticity reported in Nordin and Frankel (1980). Also, this range of variation is similar to the one studied by Bobbert (2001) as well as by Pandy, Zajac, Sim, and...
Levine (1990). The time delay in muscle activation dynamics was modeled according to He, Levine, and Loeb (1991). The activation pattern of the CE was specified with one parameter, onset time ($T_{on}$). It was assumed that the CE stayed relaxed until $t = T_{on}$, and the full neural activation signal was sent to the CE after $T_{on}$. The active state of the CE was developed as a function of the neural activation signal (He et al., 1991). A complete description of the properties of the CE, the SEE, and the activation dynamics is found in Nagano and Gerritsen (2001).

The maximal isometric force of the CE ($F_{MAX}$) was set at 6718 N, which corresponds to the maximal isometric force of the human mm. vasti (Friederich & Brand, 1990) with a specific tension of 31.5 N/m$^2$ (Brown, Satoda, Richmond, & Loeb, 1998). The optimal length of the CE ($L_{CEopt}$) was set at 0.0867 m, and the slack length of the SEE ($L_{slack}$) was set at 0.3224 m, which correspond to the values of human mm. vasti (Friederich & Brand, 1990). The mass of the inertia was set at 14.5 kg, which corresponds to the mass of a human leg (de Leva, 1996).

A simulation was started with the length of the CE and the SEE at $L_{CEopt}$ and $L_{slack}$, respectively. The optimal pattern of the neural activation input, i.e., the optimal onset time ($T_{on}$), was searched via simulated annealing numerical optimization (Press, Teukolsky, Vetterling, & Flannery, 1988). The goal of the numerical optimization was to lift the inertia as high as possible. Note that the inertia can jump higher than the maximal shortening capability of the CE if enough momentum has been provided before the CE shortens as much as 55% of the $L_{CEopt}$. $T_{on} = 0.0$ sec means that the CE is activated from the very first moment. This way, the inertia starts moving upward without a downward moving phase, which corresponds to SQJ. On the other hand, when $T_{on} > 0.0$ sec, the inertia initially moves downward, which corresponds to CMJ.

### Results

The maximal height reached by the inertia increased as the SEE elasticity increased (Table 1). Compared to a SEE elasticity of 1%, the maximal height reached by the inertia with the SEE elasticity of 7% was greater by 6.7%. This increase is attributed to the increase in net work performed by the muscle tendon complex (Table 2).

A clear difference was observed in the force developed by the CE, associated with the difference of SEE elasticity (Figure 2). Higher CE force was developed with higher SEE elasticity. The peak CE force was higher by 21.4% for the elastic SEE compared to the stiff SEE (Table 2).

For all values of SEE elasticity, 1% through 7%, a counter movement was observed in the optimal solution. A larger counter movement was observed with a higher SEE elasticity. It was also found that the optimal onset time shifted toward the later phase as SEE elasticity increased (Table 2). Although power outputs of the CE, the SEE, and the muscle tendon complex were all negative during the counter movement, the positive power output in the later phase made up for the energy loss in the counter movement phase (Figure 3) for all values of SEE elasticity (Table 2).

Compared to the suboptimal performances that were generated without a counter movement ($T_{on} = 0.0$ sec), the height reached by the inertia was greater in the optimal solutions performed with a counter movement (see Figure 4 and Table 2).
Table 1  Summary of Optimal Solution for the Explosive Activity Examined in This Study

<table>
<thead>
<tr>
<th>Stiffness parameter value</th>
<th>Stiff 1%</th>
<th>2%</th>
<th>3%</th>
<th>Normal 4%</th>
<th>5%</th>
<th>6%</th>
<th>Elastic 7%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Onset time (s)</td>
<td>0.0807</td>
<td>0.0815</td>
<td>0.0823</td>
<td>0.0831</td>
<td>0.0839</td>
<td>0.0846</td>
<td>0.0853</td>
</tr>
<tr>
<td>Max. height (m)</td>
<td>0.0629</td>
<td>0.0639</td>
<td>0.0647</td>
<td>0.0655</td>
<td>0.0663</td>
<td>0.0667</td>
<td>0.0671</td>
</tr>
<tr>
<td>Energy gain (J)</td>
<td>8.94</td>
<td>9.09</td>
<td>9.20</td>
<td>9.31</td>
<td>9.43</td>
<td>9.49</td>
<td>9.54</td>
</tr>
<tr>
<td>CESEE Neg. work (J)</td>
<td>–6.63</td>
<td>–6.68</td>
<td>–6.76</td>
<td>–6.86</td>
<td>–7.00</td>
<td>–7.07</td>
<td>–7.20</td>
</tr>
<tr>
<td>CESEE Pos. work (J)</td>
<td>15.57</td>
<td>15.77</td>
<td>15.97</td>
<td>16.17</td>
<td>16.43</td>
<td>16.56</td>
<td>16.74</td>
</tr>
<tr>
<td>CESEE Net work (J)</td>
<td>8.94</td>
<td>9.09</td>
<td>9.20</td>
<td>9.31</td>
<td>9.43</td>
<td>9.49</td>
<td>9.54</td>
</tr>
<tr>
<td>CE Neg. work (J)</td>
<td>–6.57</td>
<td>–6.54</td>
<td>–6.50</td>
<td>–6.52</td>
<td>–6.66</td>
<td>–6.50</td>
<td>–6.47</td>
</tr>
<tr>
<td>CE Pos. work (J)</td>
<td>15.52</td>
<td>15.63</td>
<td>15.70</td>
<td>15.83</td>
<td>16.09</td>
<td>15.99</td>
<td>16.01</td>
</tr>
<tr>
<td>CE Net work (J)</td>
<td>8.94</td>
<td>9.09</td>
<td>9.20</td>
<td>9.31</td>
<td>9.43</td>
<td>9.49</td>
<td>9.54</td>
</tr>
<tr>
<td>SEE Neg. work (J)</td>
<td>–0.27</td>
<td>–0.54</td>
<td>–0.84</td>
<td>–1.15</td>
<td>–1.58</td>
<td>–1.89</td>
<td>–2.30</td>
</tr>
<tr>
<td>SEE Pos. work (J)</td>
<td>0.27</td>
<td>0.54</td>
<td>0.84</td>
<td>1.15</td>
<td>1.58</td>
<td>1.89</td>
<td>2.30</td>
</tr>
<tr>
<td>SEE Net work (J)</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Note: CESEE = muscle tendon complex; CE = contractile element; SEE = series elastic element. Elasticity of the SEE was modified between 1% and 7%, where the value of 4% is accepted as the normal elasticity of SEE.

Table 2  Differences in Height Reached by the Inertia Between Optimal Solution and the Motion Without a Counter Movement

<table>
<thead>
<tr>
<th>Stiffness param. value (m)</th>
<th>Stiff 1%</th>
<th>2%</th>
<th>3%</th>
<th>Normal 4%</th>
<th>5%</th>
<th>6%</th>
<th>Elastic 7%</th>
</tr>
</thead>
<tbody>
<tr>
<td>With CM (optimal)</td>
<td>0.0629</td>
<td>0.0639</td>
<td>0.0647</td>
<td>0.0655</td>
<td>0.0663</td>
<td>0.0667</td>
<td>0.0671</td>
</tr>
<tr>
<td>Without CM</td>
<td>0.0493</td>
<td>0.0503</td>
<td>0.0513</td>
<td>0.0525</td>
<td>0.0543</td>
<td>0.0566</td>
<td>0.0592</td>
</tr>
<tr>
<td>Difference</td>
<td>0.0136</td>
<td>0.0136</td>
<td>0.0134</td>
<td>0.0130</td>
<td>0.0120</td>
<td>0.0101</td>
<td>0.0079</td>
</tr>
</tbody>
</table>

Note: The activation signal was sent to the CE from the start of a simulation.

Discussion

As series elasticity stores elastic energy when it is stretched and releases the energy when it shortens (Komi & Bosco, 1978), it is important to understand how this property functions in explosive activities. It has not yet been studied in detail just how the series elasticity functions in generating explosive activities that allow a counter movement. The first goal of this study was to examine the effects of series elasticity on an explosive activity that allows a counter movement. When
Figure 2 — Time course of force developed by the CE, with values of SEE elasticity from stiff (1%) to elastic (7%). Greater force was observed with more elastic SEE.

Figure 3 — Time course of power output from the contractile element (CE; line with circles), the series elastic element (SEE; line with crosses), and the muscle tendon complex (CESEE; solid line). Result for SEE elasticity value of 4% is shown. For other values of SEE elasticity, similar characteristics were observed with slight differences in magnitude and timing.
performing coordinated explosive activities, humans first define the goal of the activity, implicitly select the strategy for achieving the goal, and naturally perform the most suitable motion in the best way. Therefore, in computer simulation studies it is desirable to define only the ultimate goal and let the optimization process choose which type of motion should be performed. The second goal of this study was to determine whether or not a counter movement is automatically generated in an optimal explosive activity, through computer simulation and numerical optimization.

The maximal height reached by the inertia was greater with more elastic SEE (Table 1). The main message of this result is consistent with the findings of Bobbert (2001). Bobbert conducted a computer simulation study on human squat jumping (SQJ) motions in which the SEE elasticity of the mm. triceps surae was systematically modified. When the SEE elasticity was modified from 1% to 10%, increases in jump height were observed. Results of this present study confirm that the findings reported in Bobbert (2001) are also applicable to other types of motions that allow a counter movement.

The increase in work output of the muscle tendon complex, associated with the increase of SEE elasticity, is attributed to the increase in work output of the contractile element (Table 1). This increase of the CE net work output is attributed to the increase of CE force development (Figure 2). Greater force was developed with higher SEE elasticity. Greater force development resulted in greater power output, thus work output was also enhanced.

Figure 4 — Time course of the position of the inertia, with (optimal solution) and without a counter movement (CM). Results for SEE elasticity value of 4% are shown. For all values of SEE elasticity, 1% through 7%, the numerical optimization resulted in a motion with a counter movement (circle).
As the SEE elasticity increased, the onset time ($T_{on}$) shifted toward the later phase (Table 2). This indicates that a greater counter movement is preferred with higher SEE elasticity. To make the best use of SEE elasticity, an appropriate magnitude of counter movement is needed. The magnitude of the optimal counter movement increased as SEE elasticity increased. The negative work during the negative power phase was made up for by the positive work generated in the later positive power phase (Figure 3).

There were no constraints in this study that forced the computer simulation model to make a counter movement. By sending activation signals to the CE from the start of a simulation ($T_{on} = 0.0$ sec), it was possible for the model to perform the explosive activity without making a counter movement (Figure 4). However, for all values of SEE elasticity, it was found that the inertia reached greater maximal height when the activity was performed with a counter movement vs. without a counter movement (see Figure 4 and Table 2). The computer simulation model “preferred” to make a counter movement for this activity.

Kubo, Kanehisa, Kawakami, and Fukunaga (2000a, 2000b) examined the elastic properties of the m. vastus lateralis of sprinters, long-distance runners, and controls in relation to their jumping performance. It was reported that the elasticity of the m. vastus lateralis was not identical between those three groups of participants. Specifically, sprinters had more elastic tendinous structures while long-distance runners had less elastic tendinous structures. This suggests that the elastic property of the musculoskeletal system has plasticity, which can be changed through training. Results of the current study imply that it is beneficial to enhance the elasticity of the muscle tendon complex in order to improve jumping performance.

To avoid the use of a complex computer simulation model, several well-known properties of the human neuromusculoskeletal system were not considered in this computer simulation model: stretch reflex (Dyhre-Poulsen, Simonsen, & Voigt, 1991), coordination of multiple body segments (Bobbert & van Ingen Schenau, 1988), energy transfer through multiple joint muscles (Jacobs, Bobbert, & van Ingen Schenau, 1996), pennation angle of fascicles (Ichinose, Kawakami, Ito, & Fukunaga, 1998), complex activities of the central nervous system (Taga, 1995), and so on. Consideration of these factors will lead to more realistic and comprehensive examination of human motions. However, we adopted this reduction in the complexity of the model for the sake of computational load.

So far we know of no studies that used a sophisticated neuromusculoskeletal computer simulation model and let the optimization process choose whether to perform the SQJ or CMJ. Instead, two independent series of calculations have been conducted to simulate SQJ and CMJ (e.g., Bobbert et al., 1996). In a future study it will be beneficial to develop a more sophisticated neuromusculoskeletal model that receives a command such as “jump as high as possible” and chooses the best way to accomplish the goal.

To summarize, two insights were revealed through this computer simulation study: (a) A higher series elasticity, within the physiological range, results in a better performance of explosive muscular activities that allow a counter movement. This improvement in performance associated with higher elasticity is due to greater force development in the muscle tendon complex. (b) When it is possible to choose whether or not to make a counter movement, it is better to make a counter movement in order to enhance performance.
References


Acknowledgment

This study was partly supported by Integrated Rehabilitation Engineering Program, NIDRR. Akinori Nagano would like to thank Professor J.J. Collins, Center for BioDynamic, for his support.