Novel Motor Control Mechanism for Impact Absorption

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1 Introduction

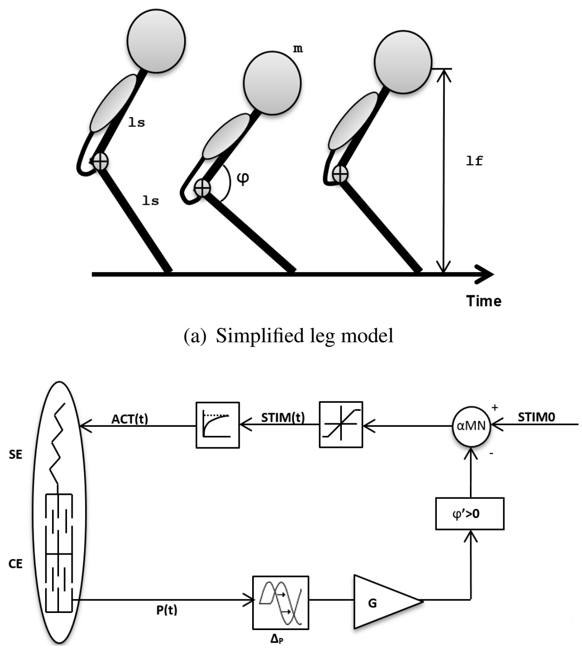
Skeletal muscles are chiefly responsible for the generation of motion in the human body. The motor control mechanisms that govern these muscles, to generate robust and stable walking and running gaits, are actively being explored in literature. Central Pattern Generation [1] and Spinal Reflex Control [2] have emerged as two viable control methodologies which, individually or in unison, best explain human locomotory control. This understanding helps in the development of robots that better mimic human walking and leg prosthetics that gel more seamlessly with the human body. Specifically, in the context of the latter, another important and useful functionality is effective drop landing from heights.

Apart from being the prime-movers of our body, muscles also act as very efficient dampers. Muscle damping behavior is actively studied to better understand leg injuries, that occur commonly due to improper falls, in sports [3]. Inspite of this wealth of literature, replete with empirical observations, little progress is made in discovering or verifying the underlying motor control mechanisms.

Our proposed motor control mechanism is motivated by two important recent findings. Firstly, in his review of motor control mechanisms [4], Santello identified two distinct neural stimuli during drop landings, namely anticipatory and reflex. While the anticipatory stimulus can be attributed to stiffening the muscle w.r.t drop height, the reflex stimulus is responsible for controlling the landing post impact. Secondly, Konow et al [5] have recently showed that tendons act as mechanical buffers to muscles to protect them from tear caused due to rapid lengthening during energy dissipation. Controlled drop landing experiments were performed on turkeys and it was observed that, the knee joint flexion caused little or no muscle fascicle stretching immediately after impact. This clearly implies that tendon acts like a series spring that quickly absorbs energy before letting the muscle dissipate it at a slower and admissible rate. The prime focus of this work is to integrate these two findings by identifying the suitable feedforward (for anticipatory signal) and feedback parameters (for reflex action), and develop a control law that best realizes these characteristics. It is shown that, for the tendon to act as a buffer and muscle to dissipate energy thereafter, a constant height-specific stimulation bias and a negative velocity feedback need to be supplied during knee flexion and extension, respectively.

2 Simplified Leg Model

Drop landing is a planar motion that is symmetric about the sagittal plane. Therefore, it is studied by first simplifying the leg model to a single leg consisting of two massless segments fitted with a point mass m at the hip. A hill-type muscle is fitted to the intrasegmental joint, as shown in Fig. 1(a). Here, l_s and l_f denote the segmental length and flight lengths, respectvely, while φ denotes the knee-joint angle. The landing dynamics of this simplified system is still indicative of the original human drop landing. It was shown in [6] that knee flexion contributed to nearly 40% of the energy dissipation. This fact justifies that the given simplified leg model, similar to the one used in [7], is an ideal to study the proposed landing control before extending it the full scale neuromuscular leg model.



(a) Simplified leg model

(b) Reflex control model

Figure 1: Leg and Muscle Models. (a) The leg has been modeled as a two segmented system with a Hill type extensor muscle. (b) The MTC consists of CE and SEE. The single sensory signal $P(t)$ is time delayed (δ_p) and gained (G) before being subtracted from a constant stimulation bias ($STIM0$) at the α-motor neuron. The resulting stimulation signal $STIM(t)$ causes muscle activation ACT(t) after a 30-40 ms delay.

The muscle tendon unit (MTU) consists of the contractile element (CE) and the series elastic element (SEE) as shown in Fig.1(b). The SEE is a passive elastic element that is connected in parallel to the muscle. This captures the tendon behavior. On the other hand, CE denotes the active muscle element. The force produced by the CE depends on muscle activation, the maximum isometric force, the force-length and the force-velocity relationship. The SEE is characterized by a non linear elastic force-length relationship. Since the CE and SEE are in series, they have equal forces acting on them. A more comprehensive understanding if this leg model can be obtained from [7]. In the next subsection, an appropriate motor control strategy is conceived.

2.1 Control Strategy

As mentioned earlier, F_{MTC} can be actively modulated through the neural stimulus $STIM(t)$. The proposed control stategy is given by equation 1. A constant stimulation bias $STIM0$ is supplied throughout the jump to account for the anticipatory neural stimulus. It is the minimum bias required to maintain the leg length at l_f, while standing. The post impact landing maneuveur can be divided into two phases, namely compression phase (knee flexion) and rebound phase (knee extension). To facilitate the tendon to first absorb the energy, it is desired that the muscle contraction is isometric. This way, it acts as a fixed end about which the tendon can be stretched by the knee flexion. Therefore, during the compression phase, no feedback is used. During the recoil phase($\varphi > 0$),however, the negative feedback term $P(t)$ is activated. Here, $P(t) = v_{CE} - v_d$, where $v_d = 0$.

$$STIM(t) = \begin{cases} STIM0, & \text{if } t < \Delta_p \\ STIM0 - G(v_{CE})(\varphi > 0), & \text{if } t \geq \Delta_p \end{cases} \tag{1}$$

3 Preliminary Results

The performance of the reflex control strategy, proposed in the previous section, is examined by dropping the leg from four different heights, $\mathbf{h} = [1.1\ 1.2\ 1.3\ 1.4]l_f$. Most importantly, the stimulation bias $STIM0$ varied for every height as $\mathbf{STIM0} = [0.5\ 0.55\ 0.58\ 0.625]$, respectively. The landing control was very sensitive to the stimulation bias. Lower values of $Stim0$ caused the system to get over-damped. The model is very sensitive to increase in the $Stim0$ as it increases the inherent elasticity of the MTU. The ground reaction force (GRF) profiles for all the heights, **h**, are shown in Fig. 2. Knee flexion occurs in $50 - 100$ ms while extension takes between $0.5 - 1.5$s. The negative feedback during extension allows, the muscle to loosen its grip in a calculative manner and feed off the energy absorbed by the tendon to pull up the leg to its standing position. The change in lengths of CE and SEE elements during knee flexion for height $h = 1.2l_f$ can be seen in Fig. 3. For a more objective comparison, their lengths are normalized. It can be seen that more than 70% knee flexion occurs between $0.2 - 0.3$s. Note that, while l_{SE} (tendon length) increased significantly during this time, l_{CE} (muscle length) remained nearly the same (a marginal drop is noted indicating a slight concentric contraction as opposed to an eccentric one). However, eventually note that, some muscle lengthening occurs before full flexion. The rate of this strectching is much lower, thereby ensuring that no damage occurs to the muscles. This behavior is clearly inline with the observations of Konow et al in [5].

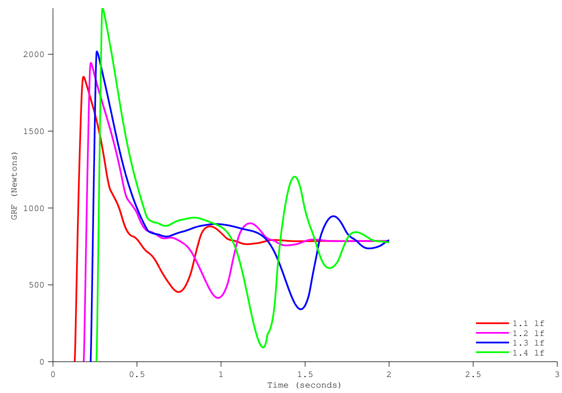


Figure 2: Ground Reaction Forces for Jump experiments with heights **h**

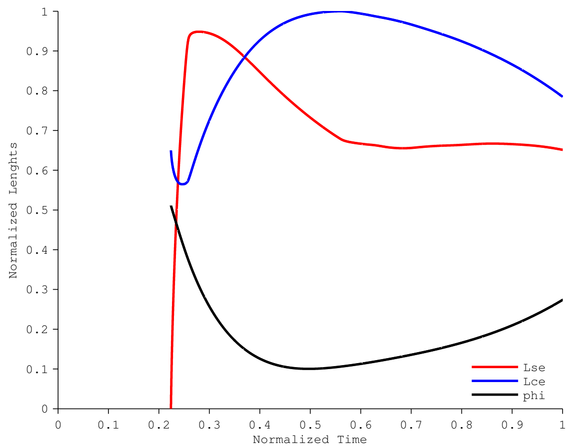


Figure 3: The elastic behavior of Muscle-Tendon Unit during Knee flexion and extension

4 Conclusions and Future Work

A novel motor control strategy was proposed to explain how anticipatory and reflex stimuli influence human drop landing mechanism. A height-dependant stimulation bias was combined with a negative feedback based reflex control in this motor strategy. While the constant stimulation bias allowed tendons to rapidly absorb energy soon after impact, the negative feedback allowed the muscle to reactively propel the leg back to its standing position without adding more energy into the system. Drop landing experiments were conducted from four diffirent heights to validate this mechanism.

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