Neuromuscular mechanism of lower limb's joint loading during normal human locomotion

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Abstract

The paper mainly, describes neuromuscular mechanism of lower limb's joint loading during normal human locomotion. First of all, a biomechanical model has developed to evaluate accurate lower limb's joint contact forces during normal human locomotion by regression method. According to author's postulate, lower limb's joint contact forces should not be greater than the ground contact force (ground reaction). It is found that maximum total contact forces of ankle joint, knee joint and hip joint during normal human locomotion are approximately, 100%, 95% and 85% of body weight of the subject respectively. Total joint contact force is compressive and tensile for respective stance phase and swing phase of human walking gait cycle. Finally, the neuromuscular activities on the joint loading clearly explained on the basis of EMG response of the subject.

Keywords: Musculoskeletal system, Lower limb's joints, Modeling, Contact forces, Neuromuscular activities

1. Introduction

Neuromuscular mechanism is a very important aspect for the study of lower limb's joint loading during normal human locomotion. Still today, the mechanism is not clearly, understood because knowledge of musculoskeletal loading of lower limb's joint during normal human locomotion is limited. In this field, most of the scientists used optimization technique to evaluate lower limb's joint contact forces. Joint contact forces are generated by combined effect of muscle forces across a joint during normal human locomotion. Theoretically, there are two category of optimization method; one is static optimization and other is dynamic optimization. The static optimization method has been used extensively to estimate in vivo muscle forces [1-6]. Also, The dynamic optimization method is used to find out in vivo muscle forces [7-9]. On the other hand, experimentally, the joint contact forces are also measured by some pioneering scientists [10-14]. Both of the two way, theoretically and experimentally, still today, it is not possible to find out the accurate value of lower limb's joint contact forces during normal human locomotion. Still now, It is reported that range of evaluated joint contact forces are within 200% to 600% of body weight during normal human locomotion whereas boundary value of joint contact force is the ground contact force (ground reaction) [13]. It is well known that the highest range of ground contact force is within 120% of body weight [15]. According to author's postulate, lower limb's joint contact forces should not be greater than the ground contact force during normal human locomotion. So, the lower limb's joint contact forces could be calculated accurately from ground contact force by regression method. Thereafter, the total contact force of the lower limb's joint would be explained on the basis of EMG response for a particular subject (person).

2. Biomechanical model

2.1 Scheme of modeling

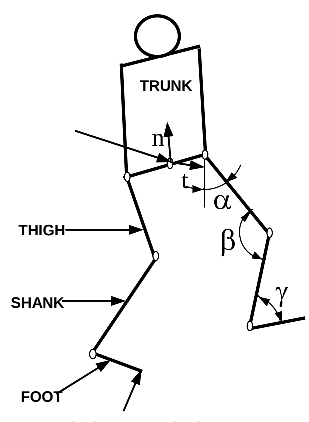

Fig. 1 Diagram of human model

Human body is modeled as a 3D system of seven segments of articulated, rigid massy linkage with 8 degree of freedom as shown in schematic diagram Fig.(1). Here, head, arms, torso and pelvis are represented as a single rigid body, trunk. The remaining 6 segments are branched out in two parts from respective two hip center and each branch part could be considered as a mechanical chain of articulated three lower limbs, thigh, shank and foot. All three joint of lower limbs have taken as a perfect hinge joint (DOF 1) to satisfy the walking in sagital plane only. According to model, it is assumed approximately that C.G. of the human body is situated on middle of the line joining two hip centers. The intrinsic coordinate system is fixed at C.G. of human body as shown in Fig. (1). The t-axis is directed forward, tangential to ground and n-axis is directed upward normal to ground. More specifically, it should be mentioned that the n-t coordinate system is selected on the basis of fundamental mechanism of human locomotion. As gravity force of body weight acts towards the center of earth normal to the earth surface (n-dir^n), so, human walking is a natural balanced process for shifting the gravity force of body weight tangential to the earth surface (t-dir^n). The 8 DOF systems consists of two DOF of center of gravity (CG) for curvilinear motion along n and t direction, and single DOF of hip, knee, and ankle joints for the angular displacement. α, β and γ represents relative angular coordinates of thigh, shank and foot respectively.

2.2 Acceleration of lower limbs

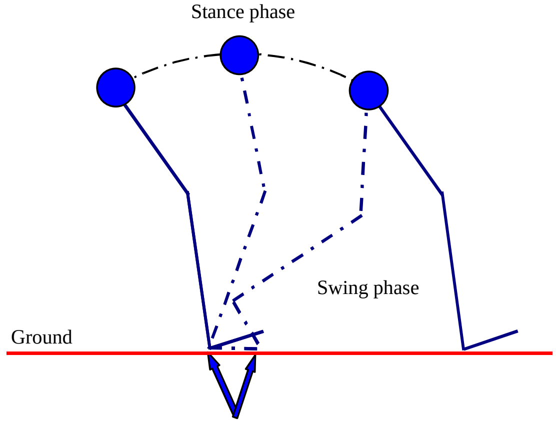

Fig.2 Line diagram of walking simulation

Human walking is a very complex balanced motion adopted from childhood naturally. It is an alternation of stance phase and swing phase cyclically for propagation of CG of human body toward forward direction as shown in Fig (2). During human locomotion foot behave like a wheel segment. So, the stance phase should be considered as clockwise rolling of CG over foot wheel with pendulum motion of lower limbs. During rolling of whole body, accelerations of lower limbs change gradually, from foot to shank and shank to thigh causing acceleration of CG in curvilinear path. Considering, over all free body diagram of human body, following equations are obtained along respective tangential and normal direction [16].

Tangential acceleration of CG = (Tangential ground reaction / body weight)*g

Normal acceleration of CG = (Normal ground reaction / body weight – 1)*g

According to assumption of modeling, as CG lies over mid point of the line joining two hip centers, so, acceleration of hip center equals to the acceleration of CG. Thereafter, components of acceleration of lower limbs could be determined in terms of generalized coordinates of thigh, shank and foot. Generalized coordinates (q_i) of respective lower limbs are expressed in term of known value of relative angular coordinate of thigh (α), shank (β) and foot (γ) with respect to vertical axis parallel to normal (n) axis through the following set of equation [equ^n 1].

$$\begin{cases} \textbf{\textit{Generalized coordinate of thigh,}} & q_1 = \alpha \\ \textbf{\textit{Generalized coordinate of shank,}} & q_2 = \alpha + \beta - \pi \\ \textbf{\textit{Generalized coordinate of foot,}} & q_2 = \alpha + \beta - \gamma \end{cases} \tag{1}$$

As during stance phase, the lower limbs are not only rotating with the rotation of CG of whole body but also,

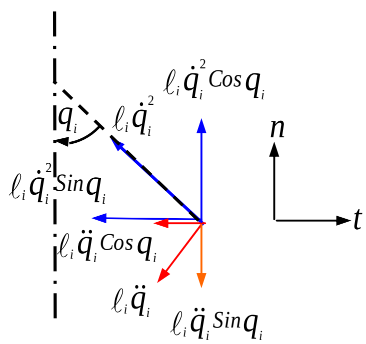

Fig. 3 Schematic accelerations of a limb

$$\begin{cases} \textbf{\textit{Tangential acceleration,}} & a_i^t = -\ell_i \ddot{q}_i Cosq_i - \ell_i \dot{q}_i^2 Sinq_i \\ \textbf{\textit{Normal acceleration,}} & a_i^n = -\ell_i \ddot{q}_i Sinq_i + \ell_i \dot{q}_i^2 Cosq_i \end{cases}$$

they follow the three limb pendulum motion, so, q_1, q_2, and q_3 will not change equally. During swing phase, three lower limbs completely, follow the three limbs pendulum motion about human CG. As CG of whole body rotates clockwise direction, the CG of lower limbs also rotates clockwise direction with respect to the CG of whole body. Generalized expression for components of a lower limb's acceleration is evaluated from the algebraic sum of components of centripetal acceleration ($\ell_i \dot{q}_i^2$) and tangential acceleration ($\ell_i \ddot{q}_i$) of the limb along the respective tangential and normal direction as shown in Fig.(3). Now, components of acceleration of thigh relative to hip joint, these of shank relative to knee joint and these of foot relative to ankle joint are evaluated for respective proximal length of thigh (ℓ_t^p), shank (ℓ_s^p) and foot (ℓ_f^p).

2.3 Dynamic equilibrium

According to model, human body is considered as seven segments of articulated, rigid massy linkage. Lower limbs consist of foot, shank, and thigh. Free body diagram of each limb is represented by gravity force, joint contact force and inertia force as shown in Fig. (4). It should be mentioned that joint moment is not shown in the free body diagram of each limb to avoid complexity of the diagram. Each lower limb must maintain the dynamic equilibrium during human locomotion. Applying Newton second law of motion for each limb along tangential and normal direction, the following equation of motion for each limb can be written.

$$\begin{cases} \sum F^t = ma^t \\ \sum F^n = ma^n \end{cases}$$

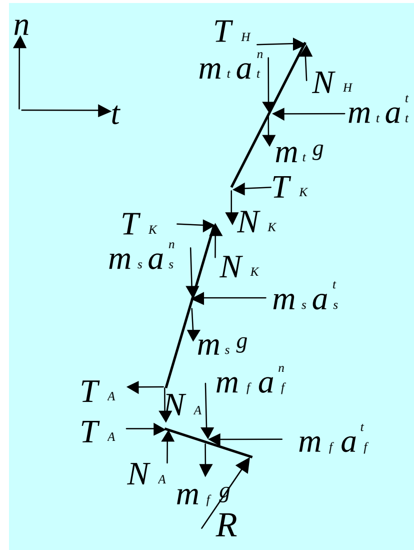

Fig.4 Force equilibrium of lower limbs

Contact force equations of lower limb's joint [eq^n 2, 3, 4] could be obtained from respective force equilibrium of lower limbs, foot, shank, and thigh.

Contact force equation of lower limb's joint

Contact force equations of ankle joint

$$\begin{cases} T_A = -[T_R - m_f a_f^t] \\ N_A = -[N_R - m_f g - m_f a_f^n] \end{cases} \tag{2}$$

Contact force equations of knee joint

$$\begin{cases} T_K = -[T_R - (m_f a_f^t + m_s a_s^t)] \\ N_K = -[N_R - (m_f g + m_s g) - (m_f a_f^n + m_s a_s^n)] \end{cases} \tag{3}$$

Contact force equations of hip joint

$$\begin{cases} T_H = -[T_R - (m_f a_f^t + m_s a_s^t + m_t a_t^t)] \\ N_H = -[N_R - (m_f g + m_s g + m_t g) - (m_f a_f^n + m_s a_s^n + m_t a_t^n)] \end{cases} \tag{4}$$

3. Input data

For input data, **subject B of A Pedotti work** is considered as a standard patient [15]. Test parameters and body parameters are taken for the subject B. Similarly, ground reaction and relative angular displacement are taken for the subject B also. Through synchronization in between ground reaction and kinematics variable, a film was taken by movie camera whose optical axis was orthogonal to the direction of propagation, during the stride on the force plate. By this way, relative angular displacements of lower limb's joints were measured [15]. Generalized angular displacements are obtained through the set eq^n 1 for the respective lower limb's joints. Thereafter, the generalized coordinates (q_1, q_2, q_3) are cubic spline curve fitted by least square method.

4. Results and discussion

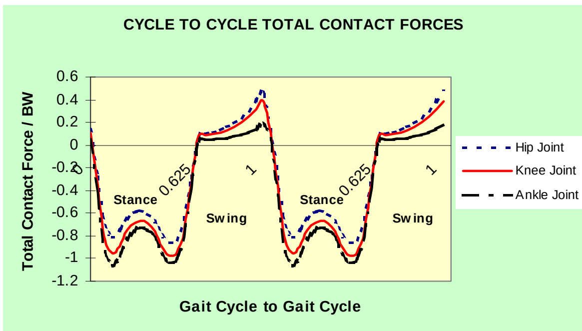

Fig. 5 Cycle to cycle total contact forces

Fig. (5), depict cycle to cycle total contact forces for ankle joint, knee joint and hip joint respectively. Total contact force is compressive and tensile for respective stance phase and swing phase of walking gait cycle of the subject. It is found that maximum total contact force of ankle joint, knee joint and hip joint are approximately, 100%, 95% and 85% of body weight of the subject respectively. Gradually, decrement of total contact force of ankle joint to knee joint and knee joint to hip joint occurs due to mainly respective gradual decrement of normal contact forces. Gradually, the normal contact forces are decreases from ankle joint to hip joint due to gradual subtraction of gravity forces and inertia forces of lower limbs that is clearly, stated in normal contact forces equations [eq^n 2, 3, 4]. Actually, compressive and tensile total contact forces are generated by muscle forces during normal human locomotion.

The neuromuscular mechanism of lower limb's joint loading during stance phase and swing phase could be explained on the basis of EMG response of each muscle. Human locomotion simulation [Fig. (2)] is drawn on the basis of relative angular displacement for he tsubject B approximately to understand the neuromuscular muscular activities on joint contact force during human walking gait cycle. EMG response is also considered for the subject B as a standard patient [15]. In the discussion stance phase is considered in two part.

Early Stance phase

From the EMG response of the subject B, it is found that Tibialis interior (TA), Semitendinosous and Semimembranosus (Hamstring, HA) muscle are active during heel strike. The TA produces compressive contact force across the ankle joint whereas HA produces compressive contact force across the knee joint and hip joint as shown in Fig. (6). As body rolls over heel wheel segment, muscle action of HA and TA increases by decreasing relative angular displacement of ankle joint and knee joint and hip joint. It results the increment of linear loading of compressive total contact force. It should be mentioned that the compressive total contact force is maximum just after heel strike causing first peak of total contact force as shown in Fig. (5).

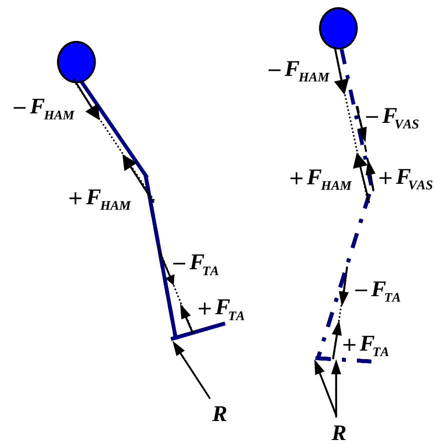

Fig. 6 Early stance phase

After heel strike, the Hamstring muscle (HA) relaxes gradually, but muscle action of Vastus medialis and Vastus lateralis (VAS) starts action on the tribofemoral knee joint [Fig. (6)] and still, compressive action of Tibialis interior continues further decrement of the dorsiflexion angle of ankle joint. Compressive action of VAS produces gradual decrement of compressive contact force due to stretching of three lower limb pendulum as shown by convex profile in Fig. (5).

Late stance phase

Thereafter, from the EMG response, it is found that TA and VAS relaxes and Gastrocnemius (GA) and Soleus (SOL) produces compressive muscle force which causes toe strike on the ground and starts rolling of whole body over the toe wheel segment. Both of the compressive muscle GA and SOL generates compressive contact force across the ankle joint whereas only GA produces similar nature of contact forces across the knee joint and hip joint [Fig.(7)] .Action of these muscle force increases again upto maximum value just after end of toe strike which causes second peak value of total contact force as shown in Fig. (5).

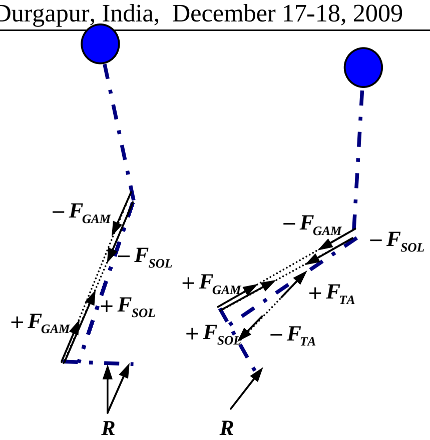

Fig. 7 Late stance phase

During toe off, Tibialis interior (TA) muscle exerts gradually, very high tensile force for lifting foot from the ground as shown in Fig. (7). The tensile TA muscle force gradually decreases compressive contact force linearly (upto zero i. e. toe off) as shown in Fig. (5).

Swing Phase

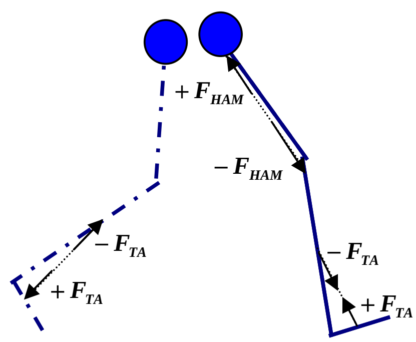

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Fig.8 Swing phase

After toe off, from the EMG response it is found that the compressive Gastrocnemius (GA) and Soleus (SA) do not produce any muscle force and only, Tibialis interior (TA) becomes active. The TA produces maximum plantar flexion of ankle joint and flexion of knee joint and hip joint by making almost like **' Z '** shape of three lower limbs just after toe off as shown in Fig.(8). Thereafter, Hamstring (HA) muscle should produce tensile action providing swing of foot and shank about the knee joint. Possibly, the tensile HA muscle force produces tensile nature of contact force across the lower limb's joint during swing phase. It should be mentioned that TA changes action from tensile to compressive at the end of swing phase for preparation of heel strike that causes starting of next stance phase.

5. Conclusion

The aim of this study was to explain the neuromuscular mechanism of lower limb's joint loading during normal human locomotion. Without optimization technique, joint contact force could be calculated accurately by regression method. It is found that maximum contact force of ankle joint, knee joint and hip joint are approximately, 100%, 95% and 850% of body weight of the subject respectively. From the EMG response of the subject, neuromuscular activities on joint loading as summarized bellow. HAM and TA develop compressive contact force to overcome ground reaction during heel strike. During mid stance phase VAS produces stretching of three lower limbs which causes slight decrement of compressive contact force of lower limb joint. Thereafter, GA, SOL, TA produces joint contact force for toe off i.e. lifting foot from the ground. During swing phase, initially, the three lower limbs are formed like Z shape by tensile action of TA and thereafter, tensile action of HA provides swing of shank and foot with respect to knee joint for smooth heel strike of foot.

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