A MODEL OF MUSCLE – TENDON FUNCTION IN THE HUMAN WALKING

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Abstract. The goal of this study is to model the muscle-tendon function as observed in the human walking. The muscle-tendon units dorsiflex the ankle, flex and extend the knee and also accelerate the joint motions. A spring model is proposed to describe the action of a unit muscle-tendon in a gait cycle of human walking. The role of the elasticity in the muscle-tendon unit activity is taken over by the set of the springs in the network model.

Key words: Muscle-tendon function, Walking, Elasticity.

1. INTRODUCTION

The elasto-viscous properties of the muscles and tendons play an important role in the human walking. The agonist and antagonistic muscles produce the flexible behavior of the joint during locomotion and a rapid storing and releasing of the energy [1–4]. Agonist muscles are responsible for the motion, while the antagonist muscles do not contract during the motion and always, they are in opposition to the agonist ones [5]. For example, the elbow flexor muscle group is the agonist for both the lifting and lowering phase. To use a mechanical analogy, the group works similarly to the pressing a pedal rapidly and immediately, the brake.

Tendons are composed by viscoelastic collagen fibres which are sometimes arranged in auxetic structures with negative Poisson's ratio [6]. Several studies demonstrated that tendons respond to changes in mechanical loading with growth and remodeling processes, much like the bones [7].

Some interesting subjects of how elasticity works in the muscle-tendon unit's activity, and how they influence the motion stability are discussed in [3] and [8]. These problems are decisive for implementation of the muscle-tendon function in the humanoid robotic systems [9, 10].

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Ro. J. Techn. Sci. – Appl. Mechanics, Vol. 64, N° 1, P. 29–36, Bucharest, 2020

Different techniques for describing the energy propagation in structures with complex geometries including curvatures, joints such as the musculoskeletal walking model, are developed in [11–13].

The gait cycle of human walking is composed by a stance phase where the foot is in contact with the ground with a temporal distribution of approximately 60%, and the swing phase where the foot is in air with a temporal distribution of approximately 40%. The stance phase can be divided into 5 segments: initial floor contact, toe off, heel rise initial contact of central limb and toe off, while the swing phase is composed by 3 segments: swinging limb, vertical tibia and initial floor contact [14–16], see Fig. 1. A general computational Ricci geometry was applied in [17] to describe the complex muscle-tendon-skeletal system acting to cycling, swimming, aquatic walking, and walking up/down the stairs.

Starting to the Endo and Herr musculoskeletal walking model, in this paper we present a model with 8 springs attached to each segment of the stance and swing phases, respectively, in the gait cycle of human walking.

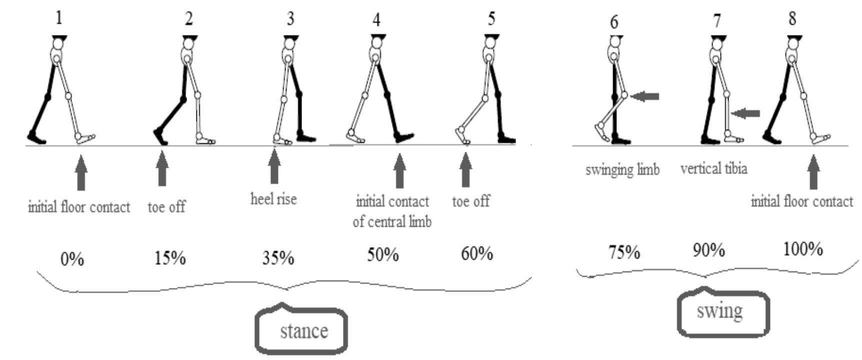

Fig. 1 – Phases of the human locomotion.

2. ESTIMATION OF THE MUSCLE-TENDON FUNCTION

The tendon-muscle unit acts as an elastic spring able to dorsiflex the ankle and flex and extend the knee. The muscle generates strength while the tendon absorbs and releases the energy. The human knee produces mechanical work in a walking cycle [18, 19]. The muscle-tendon unit is unable to dissipate this energy as heat. So, the energy is transferred through biarticular muscle-tendons to hip and the ankle joints in a walking cycle. The energy transfer reduces the mechanical work produced by the tendon-muscle unit at the hip and ankle joints.

With the above assumption, Endo and Herr [1] present a model for human walking where the muscle-tendon units dorsiflex the ankle and flexes and extends the knee. The muscle-tendon units are modeled as series elastic springs with a power source attached. The musculo-skeletal walking model proposed by Endo and Herr is shown in Fig. 2. In this model, 3 contractile muscles, i.e. the ankle plantar flexor, hip extensor and hip flexor are performing nonconservative work. The other muscles and tendons, i.e. ankle dorsiflexor, ankle-knee posterior, knee flexor, knee extensor, knee-hip posterior and knee-hip anterior are modeled as isometric muscles linked in series with an elastic tendon. Hip joint includes a 1D linear torsional spring representing the dominant hip ligament that flexes the joint.

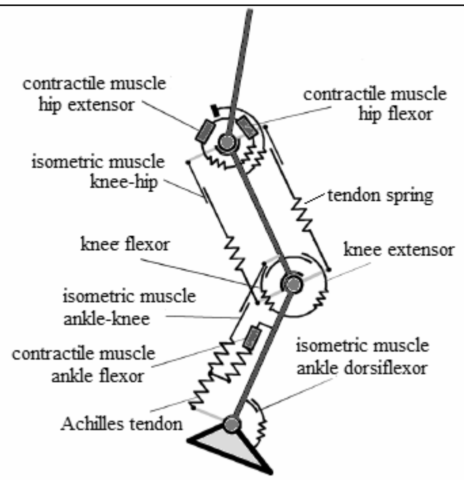

Fig. 2 – Musculoskeletal walking model, [1].

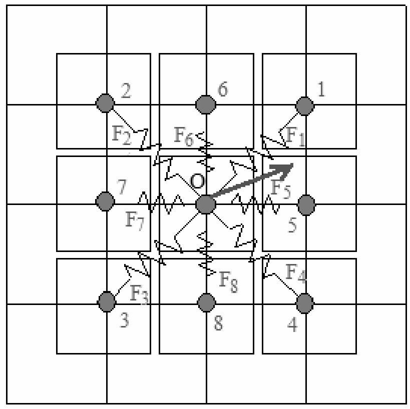

Fig. 3 – The network of elastic spring for a unit muscle-tendon.

In this paper, the model of a unit muscle-tendon is a network of 8 elastic springs, one for each segment of each phase in the gait cycle of human walking, i.e. 5 segments for the stance phase, and 3 segments for the swing phase, respectively. The network of elastic springs ensures the elastic behavior inside each segment and a perfect correlation among human walking phases. Upon muscle activation, the spring is stretched and store the elastic energy. Once the spring released its energy, its corresponding muscle became deactivated. The muscle-tendon units are modeled as unidirectional force sources, acting only in tension and never in compression. Each muscle-tendon unit is modeled using constants and values taken from the literature [20].

Fig. 3 gives a pictorial representation of the network elastic springs. The springs and elastic forces are labelled with integers from 1 to 8. The point O is mobile. Its motion represents the musculoskeletal walking model movement. It results from the simultaneous action of all 8 springs attached to all segment of the stance and swing phases, respectively, in the gait cycle of human walking.

The starting theory is the Cauchy’s equation of motion

$$\iiint_V \rho_0 \dot{v}(r,t)\mathrm{d}V = \iint_S n \cdot T(r,t)\mathrm{d}S + \iiint_V \tilde{f}(r,t)\mathrm{d}V , \tag{1}$$

where ρ_0 is the density of the body, and the Hooke's law, both in the integral form

$$\iiint_V \dot{T}(r,t)\mathrm{d}V = \iint_S \lambda n I \cdot v(r,t) + \mu\{nv(r,t) + v(r,t)n\}\mathrm{d}S , \tag{2}$$

where $v(r,t)$ is the velocity vector, $T(r,t)$ the stress tensor and $\lambda(r)$ and $\mu(r)$ are the Lamé's constants. I is the unity tensor, n the normal unit vector on S, and $\tilde{f}(r,t)$ is a volume force density.

The equations of motion of the network of elastic springs for a unit muscle-tendon are [21, 22]

$$L(x,\dot{x},\ddot{x}) + \sum_j^8 \frac{\partial U_j(x)}{\partial x} = 0 , \; j = 1,2,...,8 , \tag{3}$$

where the elastic potential $U_j(x) = \frac{1}{2} k_j x$ describes the interaction between springs, and the operator L associated with the slow motion is defined as

$$L = m\ddot{x} + k_m x , \tag{4}$$

with boundary conditions of zero displacement of the fixed end and zero force on the free end $x_0 = 0$, $x_{N+1} = x_N$. In (4) k_m is the rigidity of the mass m. The elastic forces F_i, $i = 1,2,...8$, which results from this potential are given by

$$F_i = \alpha_i f_{vi} \exp\left(k_i \left| \frac{l_i - l_{oi}}{l_{oi}} \right|^3 \right), \; i = 1,2,...8 , \tag{5}$$

where α_i is the activation of the spring i, $k_i = \lambda$ is the elastic constant of the spring i, l_i is the length of the spring i, $i = 1,2,...8$, l_{0i} is the length of the spring i in rest, f_{vi} is the force-velocity relationship for each spring given by

$$f_{vi} = \begin{cases} \dfrac{v_{\max} + v_i}{v_{\max} - K v_i}, & v_i < 0, \\ N - \dfrac{(N-1)(v_{\max} - v_i)}{\beta k v_i + v_{\max}}, & \text{otherwise.} \end{cases} \tag{6}$$

In (6), v_i is the velocity of the spring i, $v_{\max}$ is the maximum velocity, K is a constant, the force $F_{\max} = f_{vi}$ is reached for $v_i = v_{\max}$, and the number N is the ratio $N = \dfrac{f_{vi}}{F_{\max}}$.

The activation α verifies the equation

$$\tau \frac{\mathrm{d}\alpha(t)}{\mathrm{d}t} = NS(t) - \alpha(t)\,, \tag{7}$$

where τ is a time constant and $S(t) = \exp(\alpha t)$ is the neural input in the excitation-contraction interaction.

When an ankle joint performs dorsiflexes and plantar flexion movements without additional load, the points A and B move in A' and B'. Schematic illustration of the movement distances d_1 and d_2 of the joints A and B, and the joint angles θ_1 and θ_2, during the ankle dorsiflexion is shown in Fig. 4.

The relationship between displacements d_1 and d_2 and corresponding angles θ_1 and θ_2, is computed from (1–5) for $\tilde{f}(r,t) = 0$

$$d_i = \frac{1}{b_i} \ln\left[\left(\frac{\beta_i}{c_i \omega_0}\right)^2 \sin^2(a_i \theta_i) + 1\right], \tag{8}$$

with a_i, b_i, c_i, $i = 1,2,...,8$, and β are dimensionless constants depending on the elastic constant k_i, $i = 1,2,...,8$, of the springs, and $\omega_0 = \sqrt{k_m / m}$ is the characteristic frequency of the network of elastic springs with $k_m = 2.25 \times 10^9\,\mathrm{Nm}^{-2}$ and $m = 1\,\mathrm{kg}$. The values of these constants are shown in Table 1. The elasticity can amplify the power of muscle by storing the energy slowly and releasing it rapidly [24].

Figure 5 presents the relationship between displacements d_1 and d_2 and corresponding angles θ_1 and θ_2. Values ranged between $[0, 15]$ mm for d_1 and d_2, and between $[0, 20]$ degrees for θ_1 and θ_2 are taken over a random gait cycle of human walking.

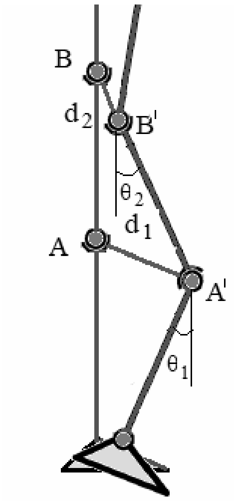

Fig. 4 – Schematic illustration of the movement distances d_1 and d_2 of the joints A and, respectively, B.

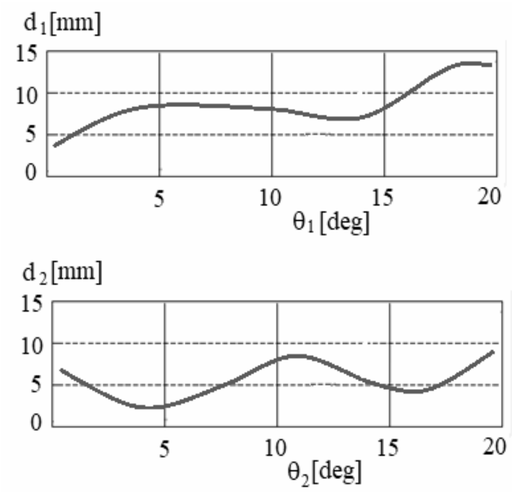

Fig. 5 – Relationship between d and θ.

Table 1

Values of a, b, c and β depending on k_i, $i = 1, 2, ..., 8$

Elastic constants	Values [Nm^{-2}]	a	b	c	β
k_1	2.24×10^9	1.01	1.22	0.29	–3.23
k_2	2.25×10^9	0.92	1.32	0.35	–2.14
k_3	2.23×10^9	0.87	1.17	0.77	–1.87
k_4	2.22×10^9	1.02	1.53	0.59	–1.73
k_5	2.22×10^9	0.89	1.04	0.34	1.14
k_6	2.25×10^9	1.02	1.35	0.75	2.05
k_7	2.26×10^9	0.95	1.12	0.92	2.43
k_8	2.26×10^9	0.99	1.22	0.72	2.02

3. CONCLUSIONS

The muscle-tendon function as observed in the human walking is analyzed in this paper. A model with 8 springs attached to each segment of the stance and swing phases, respectively, is proposed starting to the Endo and Herr musculo-skeletal model. The elastic springs model describes the action of a unit muscle-tendon in the action of dorsiflexing the ankle, the flexing and extending the knee. The role of elasticity is analyzed when the ankle joint dorsiflexes and plantar flexis without additional load. Specifically, the elastic energy in activities requiring horizontal and vertical jumps is controlling the muscular stiffness and factors which can affect the muscular stiffness such as fatigue and the avoidance of long static stretches before high-force activities.

Acknowledgements. This work was supported by the Romanian Academy. The support is gratefully acknowledged.

Received on February 24, 2020

REFERENCES

1. ENDO, K., HERR, H., *A model of muscle-tendon function in human walking at self-selected speed*, IEEE Trans. Neural Syst. Rehabil. Eng., **22**, *2*, pp. 352–362, 2014; doi: 10.1109/TNSRE.2013.2291903.
2. TORRICELLI, D., GONZALEZ, J., WECKX, M., JIMÉNEZ-FABIÁN, R., VANDERBORGHT, B., SARTORI, M., DOSEN, S., FARINA, D., LEFEBER, D., PONSs, J.L., *Human-like compliant locomotion: state of the art of robotic implementations*, Bioinspir. Biomim., **11**, *5*, 051002, 2016; doi: 10.1088/1748-3190/11/5/051002.
3. KRISHNASWAMY, P., BROWN, E., HERR, H.M., *Human Leg Model Predicts Ankle Muscle-Tendon Morphology, State, Roles and Energetics in Walking*, PLoS Comput Biol., **7**, *3*; DOI.ORG/10.1371/JOURNAL.PCBI.1001107, 2011.
4. MOŞNEGUŢU, V., *On the modeling of the human knee joint*, Revue Roumaine des Sciences Techniques, serie de Mecanique Appliquee, **53**, *2*, pp. 227–232, 2008.
5. BAECHLE, T., EARLE, R., *Essentials of Strength Training and Conditioning*, USA National Strength and Conditioning Association, 2008.
6. GATT, R., VELLA WOOD, M., GATT, A., ZARB, F., FORMOSA, C., AZZOPARDI, K.M., CASHA, A., AGIUS, T.P., SCHEMBRI-WISMAYER, P., ATTARD, L., CHOCKALINGAM, N., GRIMA, J.N., *Negative Poisson's ratios in tendons: An unexpected mechanical response*, Acta Biomater., **24**, pp. 201–208, 2015; https://doi.org/10.1016/j.actbio.2015.06.018.
7. SCREEN, H.R.C., TANNER, K.E., *Structure and Biomechanics of Biological Composites*, In: *Encyclopaedia of Composites*, 2nd Ed., Nicolais & Borzacchiello. Pub. John Wiley & Sons, Inc., 2928-2939, 2012; https://doi.org/10.1002/9781118097298.weoc015.
8. QIAO, M., ABBAS, J.J., JINDRICH, D.L., *A model for differential leg joint function during human running*, Bioinspir. and Biomim., **12**, *1*, 2017.
9. ANDERSON, F.C., PANDY, M.G., *A dynamic optimization solution for vertical jumping in three dimensions*, Computer Methods in Biomechanics and Biomedical Engineering, **2**, *3*, pp. 201–231, 1999; doi:10.1080/10255849908907988.

10. ANDERSON, F.C., PANDY, M.G., *Dynamic optimization of human walking*, Journal of Biomechanical Engineering, **123**, *5*, pp. 381–390, 2001; https://doi.org/10.1115/1.1392310.
11. SCHUBERT, F., PEIFFER, A., KOEHLER, B., SANDERSON, T., *The Elastodynamic Finite Integration Technique for Waves in Cylindrical Geometries (CEFIT)*, J. Acoust. Soc. Am. **104**, *5*, 1998; https://doi.org/10.1121/1.423844.
12. DELSANTO, P.P., WHITCOMBE, T., CHASKELIS, H.H., MIGNOGNA, R.B., *Connection machine simulation of ultrasonic wave propagation in materials. I: the one-dimensional case*, Wave Motion, **16**, *1*, pp. 65–80, 1992; https://doi.org/10.1016/0165–2125(92)90047–6.
13. DELSANTO, P.P., SCHECHTER, R.S., CHASKELIS, H.H., MIGNOGNA, R.B., KLINE, R., *Connection machine simulation of ultrasonic wave propagation in materials. II: the two-dimensional case*, Wave Motion, **20**, *4*, pp. 295–314, 1994; https://doi.org/10.1016/0165–2125(94)90016–7.
14. GOJKOVIC, Z., IVANCEVIC, T., *Control of the Extension-Flexion Cycle of Human Knees During Bicycle Riding by a Synergy of Solitary Muscular Excitations and Contractions*, Nonlinear Dynamics, **86**, *3*, pp. 2071–2080, 2016.
15. GOJKOVIC, Z., IVANCEVIC, T., JOVANOVIC, B., *A two-phase computational biomechanics model for successful rehabilitation after hip and knee surgery*, Nonlinear Dynamics, **90**, *3*, pp. 2047–2057, 2017; DOI:10.1007/s11071–017–3781–x.
16. GOJKOVIC, Z., IVANCEVIC, T., JOVANOVIC, B., *Biomechanical model of swimming rehabilitation after hip and knee surgery*, Journal of Biomechanics, **94**, pp. 165–169, 2019; https://doi.org/10.1016/j.jbiomech.2019.07.035.
17. IVANCEVIC, T., JOVANOVIC, B., GOJKOVIC, Z., *Comprehensive Review of the Universal Jolt Mechanism Theory for Musculoskeletal Injuries*, in L'Hocine Yahia (Ed.), *Ligament Reconstructions* (Chap. 12), World Scientific, Singapore, 2019.
18. WINTER, D., *Biomechanical motor patterns in normal walking*, J. Motor Behav., **15**, *4*, pp. 302–330, 1983; https://doi.org/10.1080/00222895.1983.10735302.
19. HERR, H., POPOVIC, M., *Angular momentum in human walking*, J. Exp. Biol., **211**, pp. 467–481, 2008; doi:10.1242/jeb.008573.
20. GÜNTHER, M., RUDER, H., *Synthesis of two-dimensional human walking: A test of the model*, Biol. Cybern., **89**, pp. 89–106, 2003.
21. MOŞNEGUŢU, V., CHIROIU, V., *Introducere în modelarea matematică a articulaţiei genunchiului*, Editura Academiei, 2013.
22. MOŞNEGUŢU, V., CHIROIU, V., *On the dynamics of systems with friction*, Proceeding of the Romanian Academy, Series A: Mathematics, Physics, Technical Sciences, Information Science, **11**, *1*, pp. 63–68, 2010.
23. FELLINGER, P., MARKLEIN, R., LANGENBERG, K.J., KLAHOLZ, S., *Numerical modeling of elastic wave propagation and scattering with EFIT - elastodynamic finite integration technique*, Wave Motion, **21**, *1*, pp. 47–66, 1995; https://doi.org/10.1016/0165–2125(94)00040–C.
24. ISHIKAWA, M., KOMI, P.V., GREY, M.J., LEPOLA, V., BRUGGEMANN, G.P., *Muscle-tendon interaction and elastic energy usage in human walking*, Journal of Applied Physiology, **99**, *2*, pp. 603–608, 2005; https://doi.org/10.1152/japplphysiol.00189.2005.