Introduction to Human Movement Biomechanics (ELEC-E8742)

Exam – Answer Key

Section 1: *True or False Questions*

1. The size of the cortical area (i.e., number of neurons) in the motor cortex responsible for controlling a muscle is proportional to the size of the muscle, with larger muscles having a larger cortical representation, and smaller muscles having a smaller cortical representation.

   False *– The size of the cortical area responsible for controlling a muscle in the motor cortex is not proportional to the size of the muscle. The small muscles in the forearm controlling the hand have a large cortical representation because of the fine motor control required for hand movements, while the large leg muscles have small cortical representations because they require less precise motor control. (See slide 13 in Lecture 01: Neuromuscular System Structure and Function)*

2. Concentric muscle actions produce more force, and do more positive work, if they are preceded by an eccentric action.

   True *– The stretch-shortening cycle (SSC) tells that muscles are able to produce more force and positive work when the muscle first lengthens (eccentric action) before shortening (concentric action). This increase in performance is due to a variety of factors, including elastic energy storage, spinal stretch reflex, and muscle pre-activation. (See slide 8 in Lecture 02: EMG and Muscle Mechanics)*

3. Running with a forefoot strike improves Achilles tendon elastic energy utilisation, and thus, enhances running economy.

   False *– The majority of evidence indicates that the footstrike pattern when running does not have an effect on the running economy (i.e., energetic efficiency of running). Running with a forefoot strike or heel strike does influence the biomechanical loading of the joints (forefoot strike = greater calf muscle loading; heel strike = greater knee loading), but running economy is not significantly different between footstrike patterns. In both heel strike and forefoot strike running, the leg acts as a spring to store and release energy, and this mechanism is not enhanced or inhibited between the different footstrike patterns. (See slide 30 in Lecture 05: Biomechanics of Running)*

4. During hemiplegic gait, the relative muscle efforts of the lower limb muscles are much higher on the more affected (hemiplegic) side than on the less affected (sound) side.

   False *– During hemiplegic gait the relative muscle efforts have been shown to be equal between the more affected and less affected legs. Patients with hemiplegic gait often walk with asymmetric biomechanical patterns, but the hemiplegic side is working at the same relative effort (compared to its lower maximal functional strength and capacity) as the sound side. This is likely a mechanism to reduce the loading and minimize fatigue onset for the weaker muscles in the more affected leg. (See slide 31 in Lecture 04: Biomechanics of Normal and Pathological Gait)*

5. If the internal joint moment is acting in the same direction as joint rotational movement, then joint power is positive and the joint is generating energy; while if the internal joint moment is acting in the opposite direction as joint rotational movement, then joint power is negative and the joint is absorbing energy.

   True *– When the internal joint moment and joint rotational movement are in the same direction, this means the joint angular velocity is also in the same direction with the joint moment. Based on the definition of joint power, then joint power is positive and the joint is generating energy. When internal joint moment and joint rotational movement are in opposing directions, this means joint angular velocity has an opposite sign from joint moment, and therefore resulting joint power will be negative, meaning the joint is absorbing energy. (See slide 26 in Lecture 03: Kinematics and Kinetics of Movement)*

Section 2: *Multiple Choice Questions*

6. Musculoskeletal modeling enables capabilities beyond inverse dynamics, and opens the possibility for which of the following types of analysis (select all that apply):

   e. All of the above *– Musculoskeletal modeling enables all of these types of analysis beyond inverse dynamics. (See slide 30 in Lecture 06: Wearable Assistive Technologies and Modeling)*

7. During locomotion, Achilles tendon elastic energy utilisation generates propulsive force and allows ankle plantarflexion with less:

   b. Muscle activity *– Storage and release of elastic energy in the Achilles tendon during walking means the ankle plantarflexors work more isometrically or even eccentrically, and the push-off propulsive power can primarily be produced through the release of the elastic energy stored in the compliant Achilles tendon during late stance phase. This means the plantarflexor muscles do not have to perform the fast plantarflexion movement at push-off through direct muscle action, which would require greater volume of active muscle due to the force-velocity relationship of muscle (muscle can produce much less force at faster velocities). Therefore the muscle activity of the plantarflexor muscles is reduced due to elastic energy utilisation from the Achilles tendon. (See slide 15 in Lecture 04: Biomechanics of Normal and Pathological Gait)*

8. As the Finnish winter begins, you start training cross-country skiing (an aerobic and sustained activity). As your muscles adapt to your new training, what muscle fiber type do you expect to become more common in your muscles?

   a. Type I fibers ("slow oxidative") *– Cross-country skiing is an aerobic and sustained exercise, and thus training cross-country skiing over time would trigger a shift in the muscle fiber composition to have more type I fibers. This is because type I fibers are optimized for using aerobic energy systems to regenerate the cellular energy molecule ATP (these processes rely on oxygen and are slower), and type I fibers are the most resistant to fatigue. This shift would especially be prevalent in the leg muscles that are loaded most repetitively in cross-country skiing. (See slide 22 in Lecture 01: Neuromuscular System Structure and Function)*

9. A 51kg (500 Newton) athlete is running at 10km/hr on a force-sensing treadmill. The peak ground reaction force (GRF) during running reaches 3x their bodyweight. The GRF vector at the moment of its peak is 10cm from the knee joint center, which can be taken as the lever arm distance. Assuming a patellar tendon (quadriceps) lever arm distance of 5cm, calculate the total force the quadriceps must produce. (You should not need a calculator to answer this question)

   c. 3,000 Newton *– If the GRF reaches 3x the bodyweight of our athlete, then the peak GRF = 500 N x 3 = 1,500 N. We are told the lever arm distance from the GRF vector is 10 cm (0.1 m) from the knee joint center. Therefore the external knee moment generated from the GRF = 150 Nm. We know the internal knee moment must be equal to the external knee moment because of Newton's third law. Therefore the internal knee moment is also = 150 Nm. We then divide by the provided quadriceps lever arm distance (0.05 m) to get the required quadriceps force of 3,000 N. The simplest way to compute this answer is to recognize that the external and internal knee moments must be equal, then recognize that the internal quadriceps lever arm distance is half of the external GRF lever arm, so therefore the quadriceps muscle force must be twice the external GRF to equalize the moments. (See slide 21 in Lecture 03: Kinematics and Kinetics of Movement)*

10. During the mid-stance phase of walking, when the foot is flat on the ground and the center of mass advances over the standing leg, the plantarflexor muscle fascicles are acting isometrically while the muscle-tendon unit lengthens. This leads to which of the following effects (select all that apply):

    a. The GRF vector is directed in front of or through the knee joint center *AND*
    d. Elastic energy is stored in the Achilles tendon *– During mid-stance, because the plantarflexor muscle fascicles are acting isometrically (i.e., maintaining a constant length), an internal plantarflexor moment is produced, which helps to gradually <u>shift the center of pressure under the foot from the heel to the forefoot (not from the forefoot to the heel)</u> throughout stance, and <u>directs the GRF vector in front of or through the knee joint center</u> (producing either a minimal to zero knee moment or a slight external knee extension moment, which both enable the knee to maintain extension against the thick posterior knee capsule without active knee extensor engagement) and <u>slightly behind (not in front of) the hip joint center</u> (producing a small external hip extension moment, which also enables the hip to maintain extension without active muscle engagement of the hip extensors). Because the plantarflexor muscle fascicles are acting isometrically even while the ankle dorsiflexes as the center of mass moves over the stationary foot, this means the Achilles tendon is the structure that takes up this lengthening and stretches, <u>storing the elastic energy to be released at push-off phase</u>. This process <u>does not directly prevent the loss of balance during the stance phase</u>, and other mechanisms are involved in balance control. There is an opportunity to get partial points for this question. (See slides 12 and 13 in Lecture 04: Biomechanics of Normal and Pathological Gait)*

Section 3: *Short Answer Questions*

11. When an action potential from the lower motor neuron reaches a muscle, how does this stimulate muscle contraction? Provide a brief summary of the process of muscular contraction and the steps involved, starting from the action potential arriving at the neuromuscular junction, and finishing from muscle contraction and force production. (Definitions for the various structures involved are provided at the start of the exam. You may draw diagrams to supplement your answer)

    We were looking for you to describe the process of excitation-contraction coupling that is explained in slides 18-21 in Lecture 01: Neuromuscular System Structure and Function. The process involves the following steps:

    a. *Action potential from the lower motor neuron triggers release of acetylcholine (ACh) from the neuromuscular junction (NMJ)*
    b. *ACh binds to receptors on the muscle fiber membrane*
    c. *This triggers a molecular cascade that opens sodium channels on the muscle fiber membrane*
    d. *Sodium (Na+) rushes into the muscle cell, causing depolarization (sudden change in membrane voltage) that propagates in both directions along the muscle fiber membrane from the NMJ*
    e. *This depolarization triggers the release of calcium (Ca2+) from the sarcoplasmic reticulum in the muscle fiber*
    f. *Ca2+ triggers a change in the shape of the actin myofilament that enables Myosin to bind to Actin, forming a cross-bridge*
    g. *Myosin head pulls Actin, shortening the sarcomere and contracting the muscle*
    h. *The Myosin head unbinds to Actin, and the process repeats if Ca2+ is still present to allow Actin and Myosin to bind and form another cross-bridge*
    i. *The contraction ends and the muscle relaxes when the neural signal from the lower motor neuron stops and the Ca2+ is depleted*

    You were meant to describe this process in this order. Diagrams could be used to support your explanations, but were not mandatory. A description of how this process produces muscle force, through muscle twitch summation and recruitment of many active motor units within the muscle (see slide 5 of Lecture 02: EMG and Muscle Mechanics) is also beneficial for the answer, but not required for full points.

12. What does EMG measure? When we place two electrodes on the skin over a muscle, why do we see these spiky bursts when the muscle is contracted (pictured below)? What are the components of the EMG signal?

EMG measures the electrophysiological activity of skeletal muscle (i.e., the electrical signal the muscles emanate). EMG is measuring the change in membrane voltage (depolarization) of the muscle fibers, as this depolarization travels in both directions along the muscle fiber membranes. Using surface EMG, this traveling depolarization is picked up as a waveform by electrodes placed on the skin surface over the muscle. Surface EMG is typically recorded using a bipolar configuration, where two electrodes are placed over a muscle along the line of the muscle fibers, and the signals from the adjacent electrodes are subtracted from one another along the line of muscle fiber action. This configuration reduces common noise between channels and amplifies the propagating components of the EMG signal, as the depolarization reaches the two electrodes at different times.

Imagining a single muscle fiber, the traveling depolarization would look like a symmetrical waveform with one positive peak and one negative peak. However, because each lower motor neuron synapses with many muscle fibers (together forming a motor unit), the real components of the EMG signal are the motor unit action potentials, which form a unique waveform shape determined by the distance between the NMJs and the muscle fibers that form the motor unit and the recording electrodes. In a typical contraction, many motor units are recruited at once within a muscle, and the final EMG signal is a summation of the waveform shapes from all of the active motor units. Further, based on asynchronous activation, the neuromuscular system alternates recruitment of many different motor units throughout the muscle constantly depending on the movement direction, speed, length of time needed to produce force, etc. This is why we say the EMG signal is made up of non-reproducible spikes, because it is nearly impossible that the exact combination of motor units will activate in the exact same timing/configuration again to reproduce the same spiking pattern within the EMG signal. This is why we see the spiky bursts in the EMG signal when the muscle is contracted.

The raw EMG signal also contains some noise, including power-line interference, cross-talk from other muscles or other electrophysiological tissue (like the heart) or movement artefacts. These noise components can be removed in most cases with proper experimental set up and EMG processing steps. The spiky bursts in the EMG signal contain important information about the neuromuscular activation of the muscle, and we can perform various processing and analysis steps to answer questions about the neuromuscular system using EMG, such as "how much is the muscle active?" (EMG signal amplitude), "when is the muscle active?" (measuring EMG burst duration using thresholds), or "is the muscle becoming fatigued" (based on EMG amplitude and frequency, with increasing amplitude and reduced frequency indicating muscle fatigue).

Points will be given based on whether you show that you understand what EMG measures and what the components of the EMG signal are and how they relate to the neuromuscular system and the process of muscle contraction. (See the full lecture slides for Lecture 02: EMG and Muscle Mechanics for more details)

13. What are passive dynamic walkers, and how have they contributed to our understanding of the biomechanics of walking?

Passive dynamic walkers are simple mechanical devices that can walk stably down a gradual slope. They have no motors or controllers, yet they exhibit remarkably human-like walking motions, including alternating stance and swing phases and arm swing. Passive walkers have been important models for understanding how humans minimize the energy cost of walking by using inverted-pendulum–like motion.

When the body's center of mass (CoM) reaches its highest potential energy during mid-stance, gravity then accelerates the body forward, converting potential energy into kinetic energy that peaks just before the leading leg makes initial contact. This increased kinetic energy helps the CoM rise onto the leading limb during the step-to-step transition, increasing potential energy again and preparing the cycle to repeat.

Passive dynamic walkers have also contributed to our understanding of human motor control by suggesting that much of walking motion relies on passive mechanics, with muscles activated only when needed.

(See slides 10 & 19 of Lecture 4: Biomechanics of normal and pathological gait)

Points for this question are awarded based on your description of passive dynamic walkers, and primarily what they have taught us about human walking, explicitly mentioning the inverse-pendulum model of walking, and how they show much of human walking can be maintained through passive mechanics. We noticed some students mis-interpreted this question around passive exoskeletons and assistive devices from the final lecture. We realize we could have worded the question more clearly to prevent this issue, therefore we will try to still give some partial points to these answers if they show a strong grasp of the topic of gait biomechanics and what was discussed in the assistive technology lecture.

14. Describe at least 2 of the main limitations of the Inverse Dynamics method?

While inverse dynamics is an important method for calculating joint moments to infer muscle mechanical output during movement, it has several limitations.

1. *Cannot distinguish active vs. passive joint moment components: Inverse dynamics cannot separate the moment generated by active muscle forces from that caused by passive resistive forces (e.g., friction, joint capsule, and ligament resistance). Passive resistance becomes more significant near the end of the joint's range of motion when muscles, ligaments, and joint capsule start to resist further movement. This is particularly relevant at the ankle joint.*

2. *Provides only net joint moment: The method reports the net joint moment, which often underestimates the true moment produced by agonist muscles if there is co-contraction from antagonist muscles at the same joint.*

3. *No muscle-level force sharing: Inverse dynamics does not account for how force is distributed among individual muscles within a muscle group. For example, it can estimate the moment generated by the ankle plantarflexors as a group but not by*

specific muscles such as the soleus or the medial and lateral gastrocnemius.

4. *Cannot capture two-joint muscle dynamics: The method does not provide information on how biarticular muscles transfer forces and mechanical energy between the two joints they span.*

15. Hopping, similar to running, can be modeled as a spring-mass system, where the legs act as springs to absorb and return elastic energy as the center of mass descends and rises. Design an experiment to calculate leg stiffness during hopping. Include in your answer the methods and protocol that you would use, and how leg stiffness would be computed.

    To calculate leg stiffness, information about ground reaction forces and leg length change during the contact phase of hopping is required. Ground reaction forces (GRF) can be recorded while performing the hopping task on a force plate. Ideally, one force plate per leg is used to record force application separately on each side.

    Leg length information during hopping is best obtained using motion analysis and a marker-based biomechanical model (although markerless model works well). For the leg length, the hip joint center is typically used as a proximal end-point and the centre of pressure location (i.e., the point on the ground where the GRF vector is generated) as a distal end-point. Alternatively, the distal end-point can also be another point, such as the ankle joint center or the center of the foot segment, as long as it allows determination of leg compression.

    Leg stiffness (k_{leg}) during the contact phase of hopping is then calculated as the ratio of the Peak GRF to the leg compression at the instant when this compression is maximal: kleg = Peak GRF / leg compression. (This was covered in the Analysis session 2 for the data we collected at HUS. Review the presentation slides provided in the Analysis session 2 materials to review the direct computation for how leg stiffness is computed)

    Full points for this question will require an answer that aligns with these methods and this specific equation for computing leg stiffness. However, partial points will be awarded based on the methods that are described in the answer and how well they would capture the variables necessary to compute leg stiffness (namely the GRF and leg length change during hopping). Partial points will also be awarded for leg stiffness formulas that are logical and have some basis in the biomechanical theory of the rest of the course, even if they are not exactly the correct formula.