Exoskeleton Design Considerations based on the Lower Extremity Musculoskeletal Anatomy

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ABSTRACT

This paper focuses on providing a guide for improving the understanding of how joint movement is controlled by the musculoskeletal anatomy of the lower extremities for designers of lower extremity exoskeletons and prosthetics. The lower extremity has been subdivided by the three major joints: the hip, the knee, and the ankle. For each of these joints, attention is given to which muscles control the motion or degrees of freedom with respect to these joints. Based on the published medical anatomy and physiology literature, the muscles are organized in tables by their major innervations and primary motion (flexion, extension adduction, abduction, etc.) and then by secondary and more complex motion. The provided illustrations show the location of the major flexors and extensors for the three major joints. These drawings and tables can provide a quick reference and understanding of the motion at each of the lower extremity joints, when designing intuitive and comfortable lower limb prosthetics or exoskeletons, particularly those that incorporate surface electromyography (EMG) sensors for sensing voluntary motion and machine learning (ML) for control.

Keywords: Lower Extremity Exoskeletons, Prosthetics, Human Factors, Human-Systems Integration, Musculoskeletal Anatomy

INTRODUCTION

Early lower extremity limb replacement prosthetics like artificial legs were goal oriented but limited in their function and utility and could not fully mimic or truly replace the limb (Ferris, 2017). Likewise, early exoskeletons first developed for the military and commercial sector to assist healthy individuals carry heavy loads but were limited in their ability to provide comprehensive function (Ekso, 2022). Later, lower extremity exoskeletons and prosthetics incorporated hinge joints at the ankle and knees and more degrees of freedom (DOF) at the hip joint to increase user range of motion (Ferris, 2017, Pinto-Fernandez, 2020). These exoskeletons and prosthetics, however, still did not fully emulate the human anatomy and kinematics; consequently, they produced discomfort and placed a significant metabolic demand on the user, both of which limited the time that the user could wear these devices (Ferris, 2017, Pinto-Fernandez, 2020).

Flexible exoskeletons evolved from rigid exoskeleton concepts and have more recently gained the interest of the medical community. Initially, rigid exoskeletons were made softer by covering them with protective material for safety and comfort, but later incarnations were improved with structural fabrics and flexible members replacing the rigid structural components (Asbeck, 2015). Instead of relying only upon servomotors at each joint for movement, other actuating mechanisms such as cables and pneumatic drives have allowed shifting mass and bulk from the lower extremities for both rigid and flexible exoskeletons (Veneman, 2006). Increasing the DOF at each joint has improved exoskeleton function by allowing more accurate tracking of the anatomy during movement. Exoskeleton designs have also begun to incorporate control methods developed in the prosthetic limb replacement domain, namely surface electromyography (EMG). EMG sensors have been used to detect proximal (intact) muscle activity, and more recently machine learning (ML) has been used to identify specific voluntary movement commands (Asma, 2020). This paper focuses on understanding the musculoskeletal anatomy of the lower extremities and how the joint movement is controlled by the muscles. Also, attention is given to understanding their innervation, and thus improving surface EMG placement and positioning when designing lower limb prosthetics or exoskeletons.

THE LOWER EXTREMITY JOINTS AND THEIR MOTION

Although orthopedic surgeons, anatomists, and physical therapists for decades have detailed the lower extremity human anatomy and function which generates known complex motion, exoskeleton and prosthetics designers have often oversimplified their mechanisms while engineering feasible devices with available technologies (Ferris, 2017, Moore, 1992). For example, the function and motion of the knee and ankle have often been oversimplified by ignoring the tibial and femoral rotation at the knee throughout the leg swing or the importance of eversion and inversion within the ankle for stable foot plant (Christof, 2010). Improved understanding of the lower extremity movement can make a significant difference in the function, mobility, and comfort when designing exoskeletons or prosthetics (Ferris, 2017, Moore, 1992, Pazzaglia, 2016).

The Hip Joint

The hip joint (see Table 1) is a three DOF ball and socket synovial joint between the acetabulum (socket) of the hip joint and the head of the femur (ball) (Moore, 1992). The hip joint permits flexion and extension, abduction and adduction, and rotation (internal/medial and external/lateral rotation) as well as circumduction (circular rotation of the leg which includes using flexion, extension, abduction, and adduction) (Moore, 1992, Zaffagnini, 2016, Soucie, 2011). While the narrow neck of the femur between the ball and shaft serves to allow an increase in range of motion (ROM) of the hip joint that would not be present if the femoral neck was as thick as the head of the femur, the periarticular fibrocartilage tissue and labrum limit the full ROM and contribute to increased strength and stability (Moore, 1992. Chung, 2000). As a result, the average healthy adult hip joint can flex ventrally up to 125 degrees and extend dorsally to approximately 115 degrees, whereas elderly patients have less joint ROM than younger adults and males have less ROM than females (Zatsiorsky, 2002, Kashitaro, 2017, Hemmerich, 2006). Exoskeleton and prosthetic designers can measure an individual's ROM manually with a goniometer, a simple plastic or metal measuring device with two arms forming a pivot with an angle scale. They may also often use an electronic goniometer or inertial measurement unit (IMU). Other motion capture methods may be utilized allowing recording of multiple joint angles with limb position while in motion (Moore, 1992, Zaffagnini, 2016, Soucie, 2011).

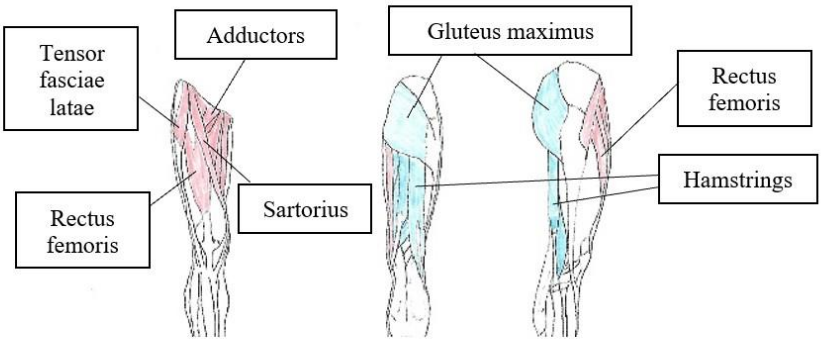
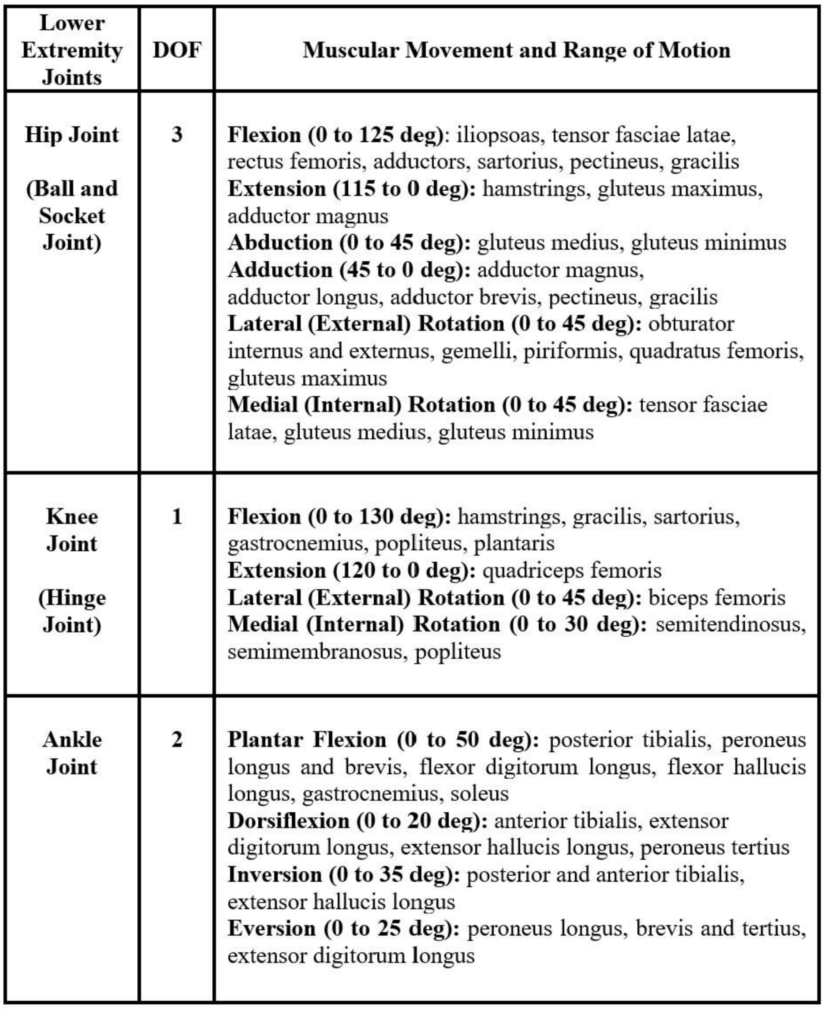


Figure 1. Anterior, posterior, and lateral views (right to left).
Hip joint flexors (red) and extensors (blue).

Three different muscle groups contribute to flexion of the hip joint (Figure 1): the flexors (quadriceps), adductors in the thigh, and the abdominal flexors, (Zaffagnini, 2016). The most important muscle is the centrally positioned rectus femoris muscle of the quadriceps femoris group (Moore, 1992). It is the largest of the hip flexors and is located within the anterior fascial compartment of the thigh, which simplifies the positioning of surface EMG sensors when assessing neuromuscular activity and voluntary hip joint flexion (Soucie, 2011).

Table 1: Summary of Muscle Action for the Lower Extremity
(Moore, 1992, Zaffagnini, 2016).



Lower Extremity Joints	DOF	Muscular Movement and Range of Motion
Hip Joint **(Ball and Socket Joint)**	**3**	**Flexion (0 to 125 deg)**: iliopsoas, tensor fasciae latae, rectus femoris, adductors, sartorius, pectineus, gracilis **Extension (115 to 0 deg):** hamstrings, gluteus maximus, adductor magnus **Abduction (0 to 45 deg):** gluteus medius, gluteus minimus **Adduction (45 to 0 deg):** adductor magnus, adductor longus, adductor brevis, pectineus, gracilis **Lateral (External) Rotation (0 to 45 deg):** obturator internus and externus, gemelli, piriformis, quadratus femoris, gluteus maximus **Medial (Internal) Rotation (0 to 45 deg):** tensor fasciae latae, gluteus medius, gluteus minimus
Knee Joint **(Hinge Joint)**	**1**	**Flexion (0 to 130 deg):** hamstrings, gracilis, sartorius, gastrocnemius, popliteus, plantaris **Extension (120 to 0 deg):** quadriceps femoris **Lateral (External) Rotation (0 to 45 deg):** biceps femoris **Medial (Internal) Rotation (0 to 30 deg):** semitendinosus, semimembranosus, popliteus
Ankle Joint	**2**	**Plantar Flexion (0 to 50 deg):** posterior tibialis, peroneus longus and brevis, flexor digitorum longus, flexor hallucis longus, gastrocnemius, soleus **Dorsiflexion (0 to 20 deg):** anterior tibialis, extensor digitorum longus, extensor hallucis longus, peroneus tertius **Inversion (0 to 35 deg):** posterior and anterior tibialis, extensor hallucis longus **Eversion (0 to 25 deg):** peroneus longus, brevis and tertius, extensor digitorum longus

The generally accepted range of motion measurements are in parentheses. Older individuals have slightly less ROM than young people. Males have less ROM than females (Center for Disease Control, 2022, Soucie, 2011)

The large femoral nerve innervates the rectus femoris and travels with the femoral artery and vein as a neurovascular bundle (see Table 2) passing into the anterior compartment of the thigh via Hunter’s Canal just deep to the sartorius muscle (Moore, 1992). Two important secondary flexors, the sartorius and iliacus muscles, both originate in the pelvis, but the iliacus inserts medially on the lesser trochanter of the proximal femur (below the femoral neck) while the sartorius crosses the knee joint to insert on the medial surface of the proximal tibia (Moore, 1992, Zaffagnini, 2016). These two muscles also contribute to control of the DOF at the hip (Soucie, 2011). The iliacus travels with the psoas major and psoas minor muscles, which both originate from the abdominal vertebral column, and all three flexors help flex the trunk as well as the thigh. Within Hunter's Canal, the femoral nerve innervates both the iliacus and sartorius muscles, just medial to the rectus femoris and quadriceps, providing an accessible location for surface EMG sensor placement (Chung, 2000). The psoas muscles, however, are directly innervated by lumbar and sacral spinal nerve branches within the abdomen and pelvis before they form the femoral and sciatic nerves (Moore, 1992).

Many of the muscles that provide smaller contributions to flexion also provide adduction and abduction. Those found in the medial compartment move the leg inward and those found in the lateral compartment move the leg outward, respectively. Some of these muscles also contribute to medial rotation (adductors) or lateral rotation of the femur (abductors) in addition to their limited contribution to flexion (Zaffagnini, 2016). Normal ROM for both adduction and abduction, as well as both medial and lateral rotation can reach 45 degrees from neutral (Zatsiorsky, 2002, Kashitaro, 2017). The obturator nerve innervates the adductors within the medial compartment, but branches of the sciatic and femoral nerves contribute to muscle group activation as well (Moore, 1992). Surface EMGs positioned over these medial compartment nerves and muscles would help characterize and assess adductor muscular activity associated with medially flexing of the thigh (Soucie, 2011). The gluteus medius and minimus muscles in the posterior pelvis together with the tensor fascia latae muscle abduct the thigh at the hip. Surface EMG sensors placed over the superior gluteal nerves that innervate these lateral compartment abductors can provide a measure of abduction activity (Moore, 1992). Lateral (external) rotation is associated with the abductors, and medial (internal) rotation correlates with the adductors respectively, but these complex motions include some degree of flexion or extension as well. It is a combination of the many muscles described within the tables that contribute to the DOFs of the hips in addition to flexion and extension (Moore, 1992).

The posterior compartment hamstring muscles (see Table 2) primarily extend the thigh at the hip joint with assistance from the gluteus maximus (Zaffagnini, 2016). The biceps femoris (short and long heads, hence biceps) is the largest and most lateral of the three hamstring muscles. This muscle originates within the pelvis and extends inferiorly to cross the knee and insert on the proximal lateral tibia, enabling it to also contribute to lateral rotation of the knee. In a similar fashion the medial hamstrings (semitendinosus and semimembranosus) both originate in the pelvis and insert below the knee at the proximal medial tibia to provide both thigh extension and medial knee rotation functionality (Moore, 1992). Surface EMGs positioned over the posterior compartment can assess the hamstring movement for extension (Zatsiorsky, 2002). The large sciatic nerve within the posterior compartment innervates the hamstrings (Chung, 2000).

The Knee Joint

The knee joint is the largest and most complicated joint of the lower extremity (see Table 1). Although structurally it resembles a hinge joint, it is a condylar synovial joint consisting of the two condyles of the femur and tibia that also includes a saddle joint between the patella and the femur (Moore, 1992). The patella, a sesamoid bone within the distal continuation of the quadriceps tendon proximal to its insertion on the proximal tibial tuberosity, resides anterior to the condyles of the femur, located distal to the patellar ligament (Eckhoff, 2005). The patella acts as a fulcrum that increases the leverage of the quadriceps muscles (rectus femoris, vastus lateralis, vastus medialis, and vastus intermedius) when extending the lower leg (Moore, 1992). The knee joint is held together by numerous ligaments and a fibrous capsule in addition to the musculature which act to stabilize and constrain the DOF of the knee (Eckhoff, 2005). The knee joint motion consists primarily of flexion and extension, however gliding and rotation occur between the tibial and femoral components throughout the leg swing (Kashitaro, 2017). At full extension, a slight medial rotation (internal rotation) of the femur occurs relative to the tibia pulling the supportive ligaments taut, thus helping to stabilize the knee while standing (Moore, 1992). The knee joint can flex up to 130 degrees to allow climbing, squatting, or kneeling, and can extend past zero (hyperextension) by a few degrees when standing (Soucie, 2011).

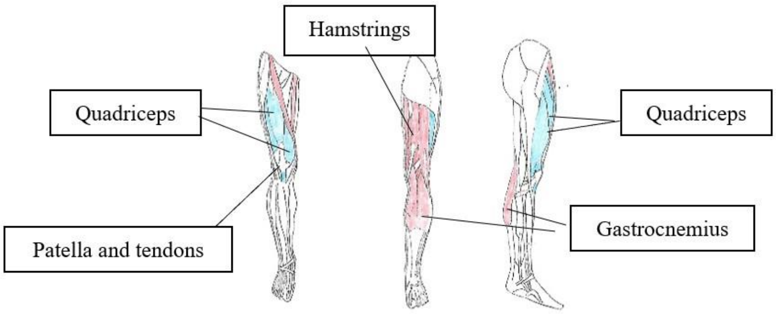


Figure 2. Anterior, posterior, and lateral views (right to left).
Knee joint flexors (red) and extensors (blue).

Within the posterior compartment (calf) of the shank of the leg (see Figure 2), both superficial (gastrocnemius, soleus, and plantaris) and deep (popliteus) muscles contribute to flexing the knee (Moore, 1992). When compared to the deeper muscles, surface EMG sensors positioned over the upper calf can more easily detect superficial muscle activation during knee flexion with a better signal to noise ratio (Posa, 2020). The inner and outer heads of the gastrocnemius muscle originate at the medial and lateral femoral condyles, respectively, and share a common insertion on the calcaneus (heel) via the calcaneal (Achilles) tendon. Crossing both the knee and ankle joints, this muscle also contributes to plantar flexion of the foot by pulling back and up on the calcaneus (Moore, 1992). The plantaris muscle also crosses the knee and ankle, originating along the supracondylar line of the lateral distal femur and inserting on the calcaneus. The lateral femoral attachment allows for medial (internal) rotation of the shank (lower leg) by pulling the posterior calcaneus laterally (Kashitaro, 2017). The popliteus, the only deep group muscle of the calf with knee flexion function, originates from the lateral condyle of the femur and the popliteal ligament posteriorly. It inserts on the upper posterior side of the tibia and medially rotates the shank as well as flexing the knee. The popliteus ligament, an extension of the semimembranosus hamstring muscle, acts as a protective membranous covering for popliteal fossa blood vessels and nerves that course behind the knee joint. All posterior calf muscles are innervated by the tibial nerve (Moore, 1992).

The hamstring musculature of the posterior thigh not only extends the thigh, but because it inserts on the tibia, it also helps to flex the knee, and rotate the shank medially and laterally (Chung, 2000). The gracilis adductor muscle in the medial thigh originates in the pelvis like the sartorius and inserts medially on the upper tibia, assisting knee flexion and medial rotation of the shank, as well as both flexion and adduction at the hip (Moore, 1992). Surface EMG sensors placed on the lower posterior thigh can detect knee flexion activation. Likewise, EMG sensors placed on the lower anterior thigh would capture the primary contribution for knee extension from the quadriceps femoris (Chung, 2000). As we can see, muscles within the lower extremity often have multiple functions adding to the complexity of motion control and indicates a need for multiple EMG sensors to improve accuracy.

The Ankle Joint

The ankle (talocrural) joint is a hinge-type synovial joint in the transverse plane between the tibia and fibula superiorly and the trochlea (pulley) of the talus inferiorly which supports plantar flexion and dorsiflexion (Moore, 1992). Inferior to the talocrural hinge joint, the intertarsal joints work together to allow for inversion and eversion at the subtalar joint. The intertarsal joints form a plane between the talus and calcaneus (heel). The transverse tarsal joint is the collective term for these intertarsal joints formed by the talus, calcaneus, navicular, and cuboid tarsal bones of the proximal foot (Chung, 2000). The talocalcaneonavicular joint is a ball and socket joint that functions together with the transverse tarsal (midtarsal) joint to manage inversion and eversion of the joint. The plantar flexion and dorsiflexion transverse axis is centered just superior to the sagittal axis of the inversion and eversion movements (Zatsiorsky, 2002).

Most of the muscles within the calf (see Figure 3) contribute to plantar flexion at the ankle talocrural hinge joint (see Table 1). These include two of the superficial muscle group (gastrocnemius and soleus) and three of the deep muscle group (flexor hallucis longus (FHL), flexor digitorum longus (FDL), and tibialis posterior (TP)) (Moore, 1992). Because the FHL inserts on the distal phalanx of the great toe and the FDL inserts on the distal phalanges of the lesser toes, these muscles also provide plantar flexion of the toes. The gastrocnemius and soleus join and form the Achilles tendon at the insertion on the calcaneus (Rivest, 2008). Of the posterior calf muscles (see Table 1), only the TP contributes to inversion of the ankle due to its many insertions on the tarsal and metatarsal bones. These posterior calf muscles are all innervated by the tibial nerve. Surface EMG sensors only need to be positioned on the calf over the distal gastrocnemius and soleus muscles just proximal to the Achilles tendon to assess plantar flexion (Takashi, 2019).

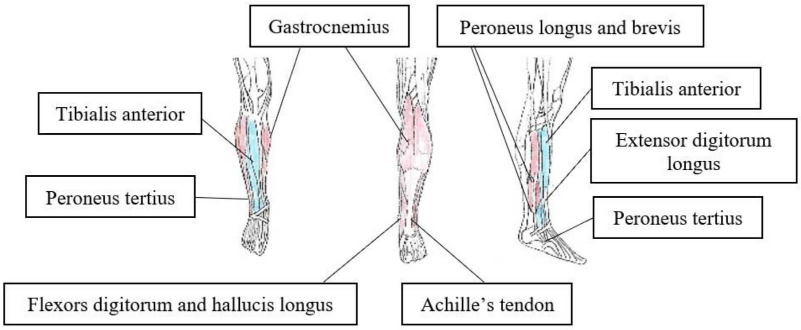
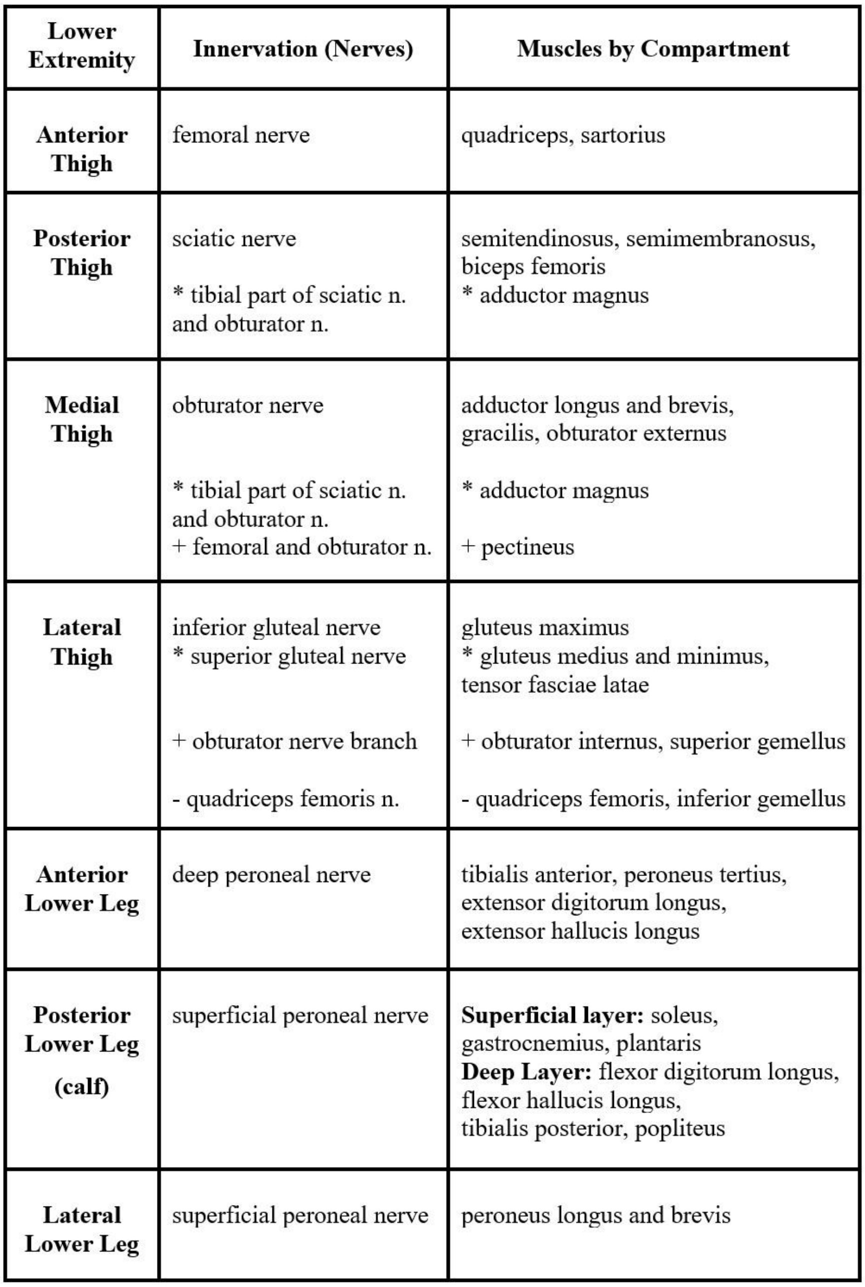


Figure 3. Anterior, posterior, and lateral views (right to left).
Ankle joint plantar flexors (red) and dorsiflexors (blue).

The peroneus longus (PL) and peroneus brevis (PB) muscles are within the lateral compartment of the lower leg and contribute to plantar flexion. The PL originates proximally at both the lateral tibial condyle and head of the fibula and descends laterally, then passes under the lateral malleolus of the ankle, and finally crosses under the foot to insert on the base of the first metatarsal bone. This allows it to generate ankle and foot eversion in addition to plantar flexion. The PB is shorter and smaller than the PL originating along the lower lateral fibula following under the longer PL. The PB however inserts medially at the base of the fifth metatarsal bone contributing to plantar flexion and some degree of eversion. These muscles are innervated by the superficial peroneal nerve and surface EMG sensors positioned over these muscles within the distal lateral leg above the ankle could help assess eversion (Chung, 2000).

All the anterior compartment leg muscles (see Table 2) are innervated by the deep peroneal nerve, and all contribute to dorsiflexion. Surface EMG sensors positioned just lateral to the ventral tibia (shin) can assess dorsiflexion (Zatsiorsky, 2002). The tibialis anterior muscle descends medially passing under the medial malleolus of the ankle to insert on the first metatarsal, thus enabling both inversion and dorsiflexion action. The extensor hallucis longus inserts on the dorsal side of the distal phalanx of the great toe and can both invert the foot and ankle and extend the great toe (Chung, 2000). The extensor digitorum longus inserts at the dorsal bases of the middle and distal phalanges of the lesser four toes contributing to foot and ankle eversion in addition to extension of the lesser toes (Moore, 1992). The smaller peroneus tertius follows the PB to the base of the fifth metatarsal and minimally contributes to eversion. The two medial anterior leg muscles invert and the lateral two muscles evert the ankle suggesting that medial and lateral surface EMG sensors placed along the anterior lower leg could differentiate between inversion and eversion, respectively, in addition to dorsiflexion (Zatsiorsky, 2002).

Table 2. Summary of Muscle Innervation for the Lower Extremity (Moore, 1992)



Lower Extremity	**Innervation (Nerves)**	**Muscles by Compartment**
Anterior Thigh	femoral nerve	quadriceps, sartorius
Posterior Thigh	sciatic nerve * tibial part of sciatic n. and obturator n.	semitendinosus, semimembranosus, biceps femoris * adductor magnus
Medial Thigh	obturator nerve * tibial part of sciatic n. and obturator n. + femoral and obturator n.	adductor longus and brevis, gracilis, obturator externus * adductor magnus + pectineus
Lateral Thigh	inferior gluteal nerve * superior gluteal nerve + obturator nerve branch - quadriceps femoris n.	gluteus maximus * gluteus medius and minimus, tensor fasciae latae + obturator internus, superior gemellus - quadriceps femoris, inferior gemellus
Anterior Lower Leg	deep peroneal nerve	tibialis anterior, peroneus tertius, extensor digitorum longus, extensor hallucis longus
Posterior Lower Leg (calf)	superficial peroneal nerve	**Superficial layer:** soleus, gastrocnemius, plantaris **Deep Layer:** flexor digitorum longus, flexor hallucis longus, tibialis posterior, popliteus
Lateral Lower Leg	superficial peroneal nerve	peroneus longus and brevis

EMG Positioning

It is not sufficient to place a single EMG sensor over the largest muscle contributing to a particular DOF, if the goal of exoskeleton design is to be comfortable and completely in sync with the user's intentions. Each motion, whether rotating the hip joint to change direction while walking, bending the knee while climbing stairs, or plantar flexing the ankle while jumping, requires a variable complex combination of muscle movements that is best defined when sensing the many muscles that contribute to the finer movements of the lower extremities (Zatsiorsky, 2002). Larger muscles will have more muscle fiber recruitment when contracting compared to smaller muscles; thus, there will be an associated stronger bioelectric signal near the belly of the muscle than near the thinner tendon and ends of the muscle (Takashi, 2019). Since individuals may vary in size and shape, elderly or weak individuals will differ in body habitus from stronger more athletic or younger individuals. Likewise, different diseases like Myasthenia Gravis can have predictable but differing patterns as well (Posa, 2020). Consequently, positioning the sensors where the bioelectric signals are detectable with sufficient confidence is important to understand the associated movements of the lower extremities (Takashi, 2019).

CONCLUSIONS AND FUTURE WORK

Exoskeleton or prosthetic limb replacement designs that do not take into consideration the actual musculoskeletal anatomy and kinematics can quickly fatigue the individual or patient secondary to high metabolic demand and discomfort (Ferris, 2017). Understanding the complex innervation, movement, and motion of the lower extremity joints and how they function can aid in the design of better and more efficient exoskeletons and prosthetic joints that meet the users' expectations and reduce metabolic fatigue. The discussion of skeletal details, the muscular innervation, the range of motion and the muscles contributing to each DOF should help facilitate and improve placement and positioning of surface EMG sensors within the exoskeleton and prosthetics designs. The exoskeleton or prosthetic designer should consider the numerous and complex combinations of muscle activity creating their EMG sensor-driven wearable robotic solutions.

A future study could examine different cohorts or groups that require an exoskeleton or limb replacement. A sensor array embedded within an ankle sock of the lower extremity could obtain EMG sensor data while walking or performing different activities of daily living, thus generating training data for a machine learning (ML) algorithm (Takashi, 2019). The ML algorithm could then be used to discern which bioelectric signal patterns are associated for specific motions of the lower extremities for these different groups of individuals. The presence or lack of reflexes could be studied as well. Finally, the ML could then auto tune to the user for more precise and personalized identification of an individual's volitional motion and intention. Using the EMG detected bioelectric signal patterns, the ML software could manage control of actuators that aid absent or weakened muscles when completing simple or complex movement. Prosthetic limbs or exoskeletons that use surface EMG arrays to sense key intentional movement would improve the comfort and usability for the user with the goal of having full and complete control of their extremities (Pazzaglia, 2016).

Electroencephalogram (EEG) or brain computer interface (BCI) treadmill gait rehabilitation (BMI) controlled exoskeletons and prosthetics have shown feasibility (Garcia-Cossio, 2015). However, duplicating the speed and function of human spinal reflexes is required to make these wearable robotic designs more useful outside the rehabilitation facility. Future work could incorporate surface EMG arrays with ML algorithms that learned to mimic movement and reflexes of the lower extremity within exoskeletons and prosthetic limb replacements. Surface EMG sensors are now sufficiently small enough to fit within clothing (Babusiak, 2018). Miniaturized versions of these sensors could even be implanted within significantly weakened muscles to improve the signal to noise ratio, detect more subtle intentional muscle activation, and improve exoskeleton or prosthesis control performance. Providing the patient with direct control and proprioceptive feedback while maintaining comfort will be key to realizing the embodiment of the exoskeleton sought by developers and healthcare providers for their patients (Ferris, 2017).

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