Ambulatory KAFOs: A Biomechanical Engineering Perspective

Kenton R. Kaufman, PhD, PE, and Steven E. Irby, MS

Individuals with proximal weakness of the lower extremity are often prescribed knee-ankle-foot orthoses (KAFOs), also known as long-leg braces, to compensate for severe weakness of the lower limb muscles. More than 1.5 million people in the United States have partial or complete paralysis of the extremities.[1] Prevalence of paralysis increases with age (Figure 1), and it is not surprising that the mobility of individuals with neuromuscular disorders is one of the most common and complicated issues treated by rehabilitation professionals. Many of these individuals require assistive technology (AT) in the form of an orthosis to enhance mobility (Table 1).[2] It is important to note that although there is a greater need for assistive technology as age increases (Figure 1), the use of AT actually decreases with age (Figure 2).[3] This usage with age is due, in part, to consumer rejection of KAFO designs.

Typically, KAFOs are extremely simple mechanically and often have few moving parts. This simplicity is accompanied by ease of donning and durability but leaves functional abilities only partially improved. Historically, KAFOs have locked the knee joint, providing stance phase stability while preventing knee motion during swing. Alternatively, KAFOs with an eccentric knee joint allow knee motion during swing but provide limited stability during stance. Either design results in inefficient gait. More recently, stance control orthoses have emerged on the market. These devices use a knee joint that is mechanically stable during the stance phase but releases for swing phase. The resulting gait is much smoother than the gait with a traditional KAFO where the knee remains locked throughout the entire gait cycle. Continued engineering development and creativity will be required for evolution of these designs into viable components for use by patients with knee instability during stance.

HISTORICAL PERSPECTIVE

In the past, two types of KAFOs were generally prescribed: eccentric (or free) knee joint and locked (or fixed) knee joint. Eccentric knee orthoses are stable in extension as long as the ground reaction force vector passes anterior to the knee hinge axis. The eccentric hinge orthosis design provides limited stance stability and allows flexion and extension to occur at all times. However, an individual must maintain the force vector anterior to the knee hinge axis during stance for stability. The eccentric knee joint provides free knee mobility during the swing phase of gait. In contrast, maximum stability is achieved in the locked KAFO. A locked knee joint orthosis keeps the knee joint straight at all times except when disengaged manually to permit knee flexion during sitting. This design allows stance phase stability but does not allow any swing phase knee mobility.

Unfortunately, KAFOs can be heavy, rigid, and frustrating devices. In practice, people who require KAFOs typically accept them for a very short period after injury or disease, but many soon reject them at rates from 60% to 80%,[4,5] presumably because walking with locked knees demands so much energy. Adding a 1.8 kg (4 lb) weight at the ankle of able-bodied subjects has been shown to increase oxygen cost (ml O_2/kg m) in level walking by 20%.[6] Similarly, locking the knee of able-bodied subjects during locomotion increases the oxygen cost by 23%.[7] Moreover, walking with bilateral KAFOs is more inefficient than wheelchair propulsion in individuals with paraplegia who require two KAFOs to walk, even for those who customarily use orthoses for locomotion.[8] These data clearly demonstrate that walking with KAFOs is much less energy efficient than typical walking, whereas wheelchair propulsion approximates the energy required for typical walking. So, it is not surprising that individuals delay or refuse to use KAFOs and select wheelchair propulsion as a primary mode of locomotion when walking with bilateral KAFOs requires far more energy.

Addition of hip joint and/or torso control creates other strata of orthoses. These would include the hip-knee-ankle-foot orthoses (HKAFO), the torso-hip-knee-ankle orthoses that include torso support, and the family of reciprocating gait orthoses (RGO). These are generally used to manage paralysis, but some may also be used in the rehabilitation setting. The knee joint has historically been locked in full extension for maximum stability with these orthoses as well.

CURRENT DEVELOPMENTS

Recently, KAFO design has been advanced by the introduction of mechanisms that provide stance phase control and swing phase freedom.[9] These are referred to as stance control orthoses (SCO). Stance phase control means that knee joint flexion is restricted during stance, the weight bearing phase of the gait cycle. These mechanisms are designed to release the knee, allowing both flexion and extension during swing, the non–weight-bearing phase of the gait cycle. The intent is to allow a more normal, energy-efficient, and cosmetically appealing gait. The potential benefits of a knee brace design that allows swing phase motion while providing stance phase knee joint control have been recognized since 1918 and are gaining attention as designs are brought to the commercial market for clinical ap-

KENTON R. KAUFMAN, PhD, PE, and STEVEN E. IRBY, MS, are affiliated with the Biomechanics/Motion Analysis Laboratory, Department of Orthopedic Surgery, Mayo Clinic, Rochester, Minnesota.

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Correspondence: Kenton R. Kaufman, PhD, PE, Biomechanics/Motion Analysis Laboratory, Charlton North L-110L, Mayo Clinic, 200 First Street SW, Rochester, MN 55905; e-mail: kaufman.kenton@mayo.edu

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