Department of Veterans Affairs

JRRD Volume 46, Number 2, 2009
Pages 257–268
Journal of Rehabilitation Research & Development

Engineering design review of stance-control knee-ankle-foot orthoses

Terris Yakimovich, MASc;[1] Edward D. Lemaire, PhD;[1*] Jonathan Kofman, PhD, PEng[2]
[1]Institute for Rehabilitation Research and Development, The Ottawa Hospital Rehabilitation Centre, Ottawa, Canada; [2]Department of Systems Design Engineering, University of Waterloo, Waterloo, Canada

Abstract—Persons with quadriceps muscle weakness are often prescribed a knee-ankle-foot orthosis that locks the knee in full extension during both stance and swing phases of gait. Locking the knee results in abnormal gait patterns characterized by hip hiking and leg circumduction during swing. The stance-control knee-ankle-foot orthosis (SCKAFO), a new type of orthosis, has emerged that permits free knee motion during swing while resisting knee flexion during stance, thereby supporting the limb during weight-bearing. This article examines various SCKAFO designs, discusses the existing design limitations, and identifes remaining design challenges. Several commercial SCKAFOs have been released that incorporate different locking mechanisms. Preliminary gait studies have shown some devices to be promising; however, an important functional limitation in some SCKAFOs is dependence on specific joint angles to switch between stance and swing modes. Important design factors such as size, weight, and noise must be considered in new orthosis designs to ensure wide consumer acceptance.

Key words: assistive technology, design, gait, knee-ankle-foot orthosis, lower limb, orthosis, rehabilitation, stance, stance control, stance-control knee-ankle-foot orthosis.

INTRODUCTION

Approximately 866,000 Americans use a lower-limb orthosis [1]. For people with isolated quadriceps weakness or paralysis, a standard knee-ankle-foot orthosis (KAFO) is typically prescribed to support the limb during locomotion. Many of these KAFOs support the limb by locking the knee in full extension throughout the gait cycle to prevent the leg from collapsing while weight-bearing.

While constraining the knee to full extension solves the body-weight support problem, straight-legged gait introduces other issues. During swing phase, KAFO users must adopt unnatural gait strategies to bring their braced leg forward to prepare for the next heel or foot strike. Compensatory gait patterns include increased upper-body lateral sway, ankle plantar flexion of the contralateral foot (vaulting), hip elevation during swing phase (hip hike), or leg circumduction [2]. Lack of knee flexion during foot strike causes abrupt initial loading and disrupts the smooth progression of the center of mass (COM) of the body.

Abnormal gait patterns can lead to soft tissue and joint dysfunction of the hip and lower back, causing pain and loss of motion [3]. As well, walking with a fixed knee can decrease gait efficiency by 24 percent [4] and increase vertical displacement of the COM of the body by up to 65 percent [5]. The associated increased muscular effort can lead to higher energy expenditure [6] and early fatigue for the KAFO user during ambulation [4]. Increased energy demand with the KAFO contributes significantly toward high KAFO rejection rates (between 60% and almost 100%) [6].

Abbreviations: AFO = ankle-foot orthosis, COM = center of mass, DKBS = Dynamic Knee Brace System, KAFO = knee-ankle-foot orthosis, SCKAFO = stance-control knee-ankle-foot orthosis.

***Address all correspondence to Edward D. Lemaire, PhD; Institute for Rehabilitation Research and Development, The Ottawa Hospital Rehabilitation Centre, 505 Smyth Road, Ottawa, Ontario, Canada K1H 8M2; 613-737-7350, ext 75592; fax: 613-737-4260. Email: elemaire@ottawahospital.on.ca**
DOI:10.1682/JRRD.2008.02.0024

When the knee cannot flex, ascending and descending stairs and inclined surfaces and walking onto curbs pose challenges. Walking with a fully extended knee hinders balance correction when a user stumbles, since the leg cannot flex to control fall direction and the braced limb cannot dampen the fall [7].

Attempts have been made to design a new orthosis that would improve gait over conventional locked-knee KAFOs. However, several difficult design challenges hindered efforts to solve this problem. Recently, a new type of KAFO has emerged on the orthotics market that allows wearers to flex their knee when swinging the leg forward while preventing knee flexion during weight-bearing. These new designs have been commonly labeled stance-control knee-ankle-foot orthoses (SCKAFOs) in the orthotics community. SCKAFO designs must ensure proper functioning during stance and swing, as well as appropriate switching between weight-bearing and non-weight-bearing modes. This article examines the design challenges of these new SCKAFO devices and compares various design approaches.

STANCE-CONTROL KNEE-ANKLE-FOOT ORTHOSIS INDICATIONS

An appreciable portion of the population using fixed-knee KAFOs has sufficient hip strength to benefit from a SCKAFO. SCKAFO prescription criteria typically require hip strength of at least Grade 3*. This includes people with multiple sclerosis, muscular dystrophy, polio, post-polio syndrome, spina bifida, incomplete spinal injury, unilateral leg paralysis and paresis, trauma, congenital defects, and isolated quadriceps weakness. Hip strength and control requirements may decrease for some SCKAFO designs as prescribers gain experience with clinical use of these devices.

Some studies have suggested that orthoses that allow uninhibited knee motion in swing improve gait kinematics and increase gait efficiency compared to conventional KAFOs. McMillan et al. analyzed gait patterns and heart rates of three subjects with lower-limb weakness walking with a SCKAFO built by Horton Technology, Inc [3]. The subjects participated in a series of gait analysis and treadmill trials and an obstacle course. The study reported faster walking speeds, longer strides, fewer compensatory motions, increased mobility, and more symmetrical gait patterns when subjects walked with a SCKAFO than with a fixed-knee KAFO. Hebert and Liggins reported similar results for level ground walking by a post-poliomyelitis syndrome subject using a Horton SCKAFO, although spatiotemporal parameters only showed small changes [8]. Zissimopoulos et al. investigated nine nondisabled subjects walking with the Horton SCKAFO in locked-extension, free-swing, and stance-control modes [9]. No significant difference in oxygen consumption was observed between subjects walking with the SCKAFO in locked-extension mode and stance-control mode; however, subjects experienced closer to normal gait kinematics when walking with the SCKAFO in stance-control mode than in locked-extension mode.

Lehmann and Stonebridge investigated the effect of a SCKAFO on the oxygen consumption of two nondisabled subjects and two patients with spinal cord lesions [10]. Significant energy savings were reported for nondisabled subjects at ambulation rates >73 m/min. However, energy expenditure improved little in both disabled subjects, since they did not have sufficient muscle strength to flex their knee adequately in the swing phase or sufficient hip flexor strength to reach normal walking speeds. Other SCKAFO-KAFO oxygen consumption comparisons with nondisabled subjects showed no significant differences [6,9]. Kaufman and colleagues showed a 1 mL/kg/mm improvement in oxygen consumption when a subject with post-polio syndrome used a SCKAFO compared with a KAFO [6]. For nondisabled individuals, this change increased walking velocity 8 m/min.

Another study investigated the effect of a SCKAFO on lower-body kinetics and kinematics of eight novice KAFO users and thirteen experienced KAFO users [11]. Walking with the SCKAFO, the novice users increased self-selected walking velocity and stride length significantly compared with experienced users. One explanation may be that the accommodation period with the Dynamic Knee Brace System (DKBS) may not have been long enough to overcome the learned walking strategies used for the conventional KAFO. Both novice and experienced KAFO users increased peak knee flexion in

---

*This value comes from prescription criteria provided by various manufacturers in unpublished documents and manuals:
- Becker Orthopedics Stance Control Overview Guide II, p. 4.
- Fillauer Swing Phase Lock Manual, p. 4.
- Horton Stance Control Knee Training Course.
- Otto Bock Sensor Walk (http://www.ottobock.ca/cps/rde/xchg/ob_us_en/hs.xsl/15994.html).

swing and reduced compensatory motions such as plantar flexion of the contralateral ankle in stance (vaulting) and dynamic pelvic obliquity (hip hike). In another study, consumers found that the SCKAFO offered them greater stability while standing and walking compared with their original orthosis [12]. A study involving 14 participants walking with the DKBS, 3 months into an open-enrollment field trial, found that temporodistance measures improved significantly [13].

Research has shown improvements in mobility and walking with the SCKAFO compared with fixed-knee KAFOs. The results suggest a strong potential for wider prescription and SCKAFO use if the design meets important functional and cosmetic needs of orthosis users.

DESIGN CONSIDERATIONS

A SCKAFO should allow free knee motion in the swing phase and resist knee flexion at any knee angle in the stance phase. The orthosis should also allow users to extend their knee at any time in stance mode to permit the user to climb onto a curb or stair or to recover from a stumble. The ideal orthosis should also be quiet, have a very quick reaction time (<6 ms) when switching between stance and swing modes [14], be relatively inexpensive to manufacture, function reliably for an appreciable amount of time between servicing (>6 mo) and recharging with an electric power source (at least 1 day of use, if electromechanical), and support a large segment of the potential user population.

The SCKAFO has remained a challenging engineering problem because of the high-flexion moments that occur at the knee during normal walking cadence (1.04 Nm/kg body mass) [15], fast cadence (1.67 Nm/kg) [15], and stair climbing (1.71 Nm/kg) [16]. The knee joint, or other structural mechanism, must support these high-flexion moments. An ideal orthosis should also have minimal dimensions mediolaterally and anteroposteriorly and be as lightweight as possible. Since a regular KAFO can weigh 5 lb (2.3 kg), a SCKAFO should be at least as light as the typical KAFO. This design is a difficult challenge, since knee-joint components that sufficiently resist failure and are sufficiently safe are not typically light and small. The following section describes SCKAFO devices that are on the commercial market or published recently in journals.

CURRENT STANCE-CONTROL KNEE-ANKLE-FOOT ORTHOSES

Otto Bock Free Walk/Becker UTX

Manufactured by two different companies under two different names, Otto Bock HealthCare's Free Walk and Becker Orthopedic's UTX share the same ratchet/pawl design [17–18] (**Figure 1**). A spring-loaded pawl locks the knee automatically when the knee fully extends prior to heel strike (**Figure 1(a)**). A 10° ankle dorsiflexion angle causes a control cable connected to the pawl to pull down and disengage the lock (**Figure 1(b)**). Simultaneous extension of the knee with 10° dorsiflexion is required to eliminate flexion moments about the knee and free the pawl from friction for disengagement.

Since full knee extension is required to engage the knee lock, the knee will be unsupported if flexed during limb loading. Limb loading on a flexed knee is common when users walk on stairs, inclines, uneven ground, or during stumbling and relaxed standing. Since the disengagement mechanism requires 10° dorsiflexion, the device cannot be used for patients with a fused ankle or biomechanical problems that limit dorsiflexion. The Otto Bock Free Walk/Becker UTX is the lightest and most cosmetically attractive of all commercial SCKAFOs; however, the delicate tubular steel structure could concern users who feel they need more support.

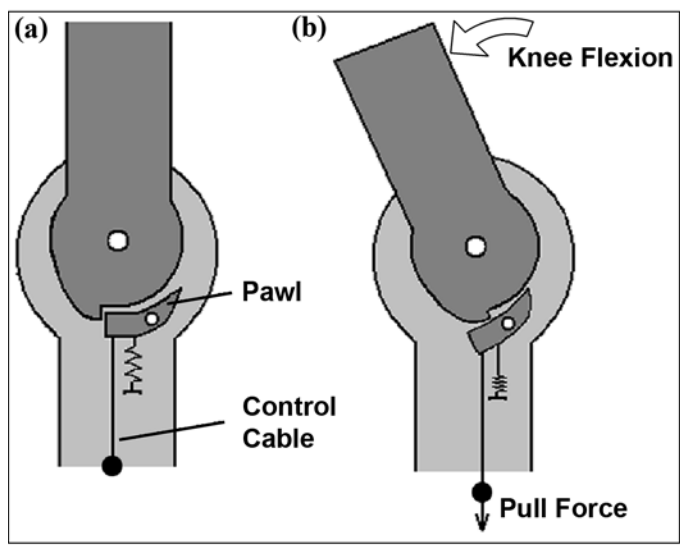

Figure 1.
Otto Bock Free Walk/Becker Orthopedic UTX. **(a)** Spring-loaded pawl locks knee when full knee extension is attained. **(b)** Dorsiflexion of foot at end of stance pulls on control cable connected to pawl to disengage lock for swing.

Horton Stance Control Orthosis

Horton Technology, Inc, produces the Horton Stance Control Orthosis (**Figure 2**), that features a locking mechanism modeled after a standard unidirectional clutch design and involves jamming an eccentric cam into a friction ring that is attached to the upper-knee joint (**Figure 3**) [19–22].* A thermoplastic stirrup shell (**Figure 2**) is positioned just below the thermoplastic ankle-foot orthosis (AFO) shell. The thermoplastic stirrup travels along the length of the orthosis and is attached to a pushrod that is attached to the eccentric cam.

Heel contact pushes the stirrup upward to engage the pushrod and drive the cam into the friction ring. The surface of both the hardened steel cam and friction ring is textured with microgrooves. These microgrooves eliminate slip between the friction ring and cam. When the cam is engaged, knee flexion causes the friction ring to load the cam, thereby locking the joint. Knee extension pushes the cam away from the friction ring, allowing uninhibited knee extension. During limb unloading, a spring pushes the pushrod down, the cam disengages, and the knee can move freely. An extension moment about the knee is required to eliminate impinging forces on the cam and disengage the joint. Attaching the pushrod to the heel of an articulated AFO section can actuate the Horton Stance Control Orthosis locking mechanism. When the foot plantar flexes, the cam will push upward to engage the lock. A knob located on the side of each joint will switch the joints into one of three functional modes: automatic stance/swing, constant free knee motion, and constant locked knee extension. These different modes add versatility to the orthosis. Constant locked knee extension can add security for orthosis users walking in unsure surroundings, and the free knee motion mode facilitates activities such as using the gas and brake pedals while a car is being driven.

The Horton Stance Control Orthosis is bulky, and the joints are relatively large by KAFO standards, with a mediolateral profile of 2.3 cm. While this design can lock at any knee angle, some users may not tolerate the bulk of this SCKAFO.

Both mechanical actuation methods for the Horton Stance Control Orthosis can be problematic. Objects such as clothing, socks, or debris from walking outdoors can lodge between the foot and the stirrup. The two-layer thermoplastic foot shell may prevent the user from donning a shoe or the shoe may adversely affect the stirrup mechanism. The articulating ankle-driven pushrod option cannot be used for users with ankle mobility problems. The sensitive triggering mechanism may constrain users to walk with a consistent step length and speed to achieve reliable engagement [9]. This SCKAFO can also fall out of the optimal performance-trimmed state, leading to unreliable locking performance.

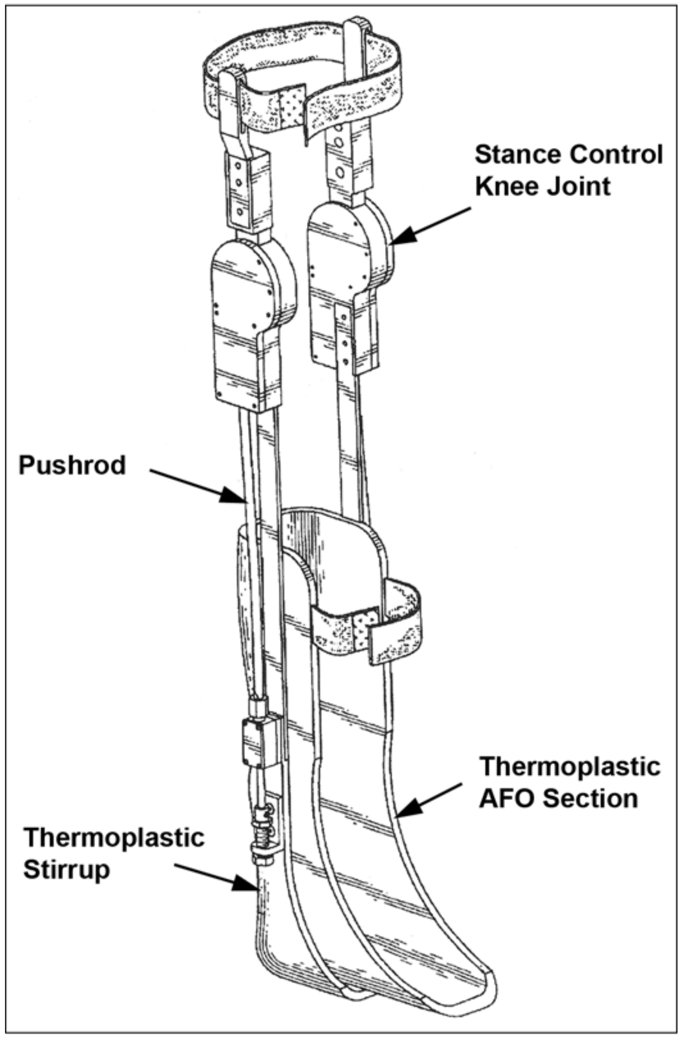

Figure 2.
Horton Stance Control Orthosis. Hatton BJ, Hatton DL, Wallace ZG. 2003. Articulating knee supports. United States patent US 6635024. 2003 Oct 21. AFO = ankle-foot orthosis.

Fillauer Swing Phase Lock

Fillauer, LLC, developed a novel gravity-actuated knee-joint locking mechanism for its Swing Phase Lock

*Drachlis D. Innovative knee brace moves a step closer to manufacturing with acceptance of final design. Marshall Space Flight Center News Release 98–032. 1998 Mar 5.

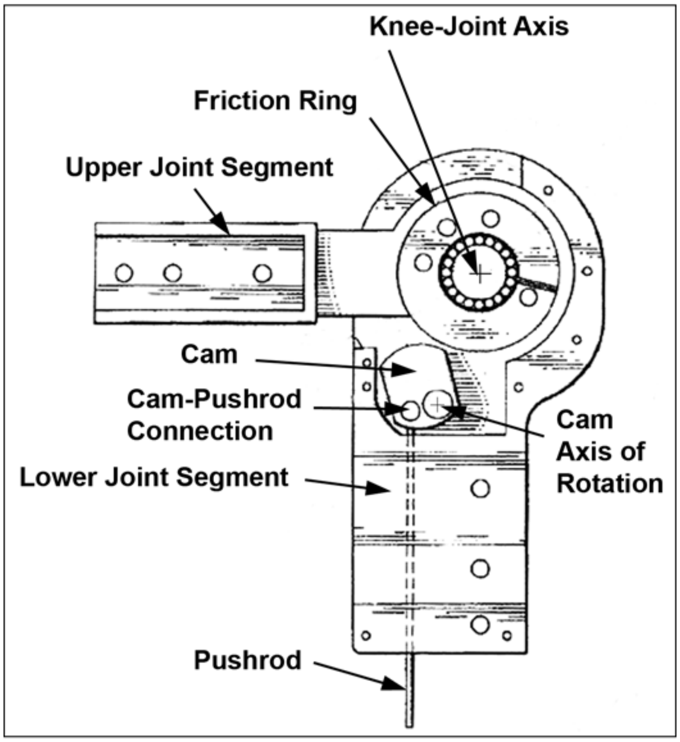

Figure 3.
Cross-sectional view of Horton Stance Control Orthosis locking mechanism—unlocked and in 90° knee flexion. Hatton BJ, Hatton DL, Wallace ZG. 2003. Articulating knee supports. United States patent US 6635024. 2003 Oct 21.

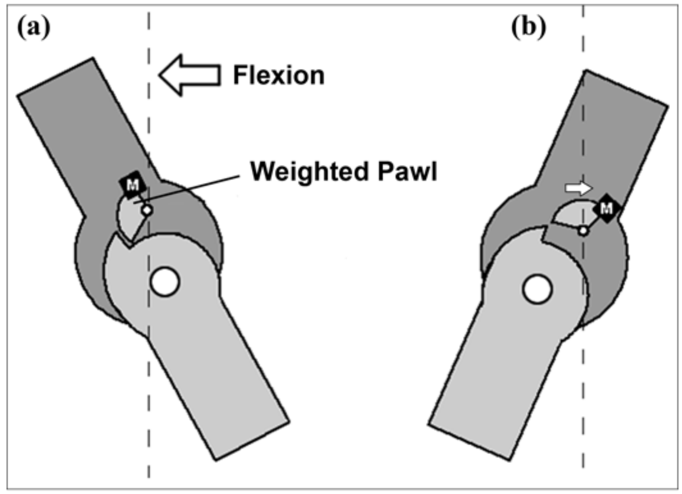

Figure 4.
Gravity-activated Fillauer Swing Phase Lock with pawl weighted by mass (M): **(a)** when thigh is anterior to user's body and knee is fully extended, weighted pawl falls into locked position; **(b)** with thigh posterior to user's body and knee extension moment, pawl falls out of engagement.

orthosis [23]. As shown in **Figure 4**, a weighted pawl falls in and out of locking position, depending on the user's thigh angle.

When the hip is flexed with the thigh anterior to the body, as in terminal swing, the weighted pawl falls into the locked position to prevent knee flexion (**Figure 4(a)**). The knee must be fully extended for the pawl to fall into this locked position. When the hip swings behind the body prior to the swing phase, the weighted pawl disengages and the knee flexes freely (**Figure 4(b)**). An extension knee moment is required to eliminate impinging forces on the pawl and allow the pawl to disengage freely. The hip angle required to engage and disengage the pawl is manually set on the joint head by an orthotist. Only one Fillauer Swing Phase Lock is mounted on the KAFO. The second orthotic knee joint, mounted on the medial side of the KAFO, is a simple mechanism that uses friction and a spring to regulate knee flexion in the swing phase [24]. A satellite switch, fixed to the proximal end of the orthosis, switches the functional knee joint into one of three operational modes: manual lock, free swing, and automatic lock/unlock [25]. Since the locking mechanism depends on limb-segment orientation, the Fillauer Swing Phase Lock is not effective for users to securely climb stairs or walk on uneven ground.

Becker Orthopedic 9001 E-Knee

The Becker Orthopedic 9001 E-Knee uses a magnetically activated one-way dog clutch (**Figure 5**) [26]. The joint integrates two circular ratchet plates that are spring-biased apart. One of the ratchet plates is positioned within an electromagnetic coil. When pressure sensors below the foot detect foot contact, the electromagnetic coil is energized and the ratchet plates are forced together. When engaged, the ratchet plates allow relative angular motion in only one direction. In stance, knee flexion is resisted, while knee extension is still allowed.

Ratchet devices suffer from two inherent disadvantages. First, as in a household ratchet tool, the 9001 E-Knee generates a clicking sound when rotated under engagement, such as when users extend their knee in stance. Cosmetics are often as equally important as function for KAFO users. If an orthosis looks or sounds unnatural, the orthosis may not be used.

Second, unlike most friction-based clutches, a ratchet device only has a finite number of locked positions. The 9001 E-Knee houses 60 ratchet teeth, thereby allowing up to 6° of free-fall knee flexion before the joint locks

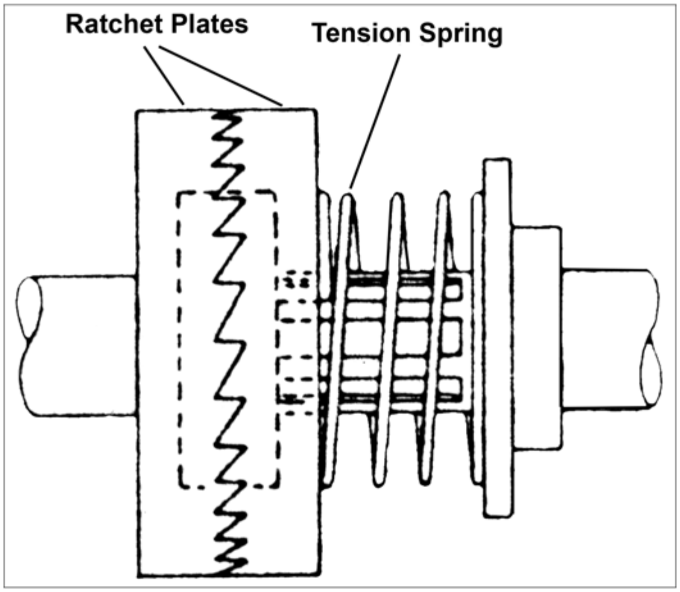

Figure 5.
One-way dog clutch: Becker Orthopedic 9001 E-Knee integrates dog clutch into its design where ratchet plates are spring loaded to separate. Surrounding electromagnetic coil works against spring to engage plates in stance.

into position [27]. Users who require the confidence of a rapidly engaging knee lock may not tolerate this motion.

The bulky nature of the 9001 E-Knee adversely affects the cosmetic appeal of the orthosis and may be obtrusive for some users. The electromagnetic coil makes the 9001 E-Knee a relatively heavy SCKAFO joint. Also, the cost of the 9001 E-Knee is relatively high compared with other SCKAFO joints.

Dynamic Knee Brace System

Kaufman et al. advanced SCKAFO technology by reintroducing electromechanical knee-joint control [6]. The DKBS uses a conventional unidirectional-clutch actuated with pressure sensors beneath the heel and forefoot to detect heel strike and rise [6,11,28–29]. An onboard microprocessor interprets signals from both the pressure sensors at the foot and a sensor at the knee joint measuring knee angle to control a solenoid that engages and disengages a wrap-spring clutch built into the knee joint [28].

The wrap-spring clutch uses a close-wound helical spring to transmit torque across a pair of mating concentric clutch hubs. When the knee attempts to flex, the spring tightens over both concentric hubs, thus preventing knee flexion by stopping relative motion between the two hubs. Knee extension causes the spring to unwind and allow relative motion of the two hubs. To disengage the clutch selectively in swing, the spring is loosened by pulling back on one end of the spring via a solenoid. The wrap-spring clutch has the unique ability to switch from stance to swing mode while loaded in flexion. The joint mechanism therefore demands less mental and physical effort from the user to control the orthosis than SCAKFOs that require a knee extension moment to switch from stance to swing mode. The wrap-spring clutch knee joint has a braking capability of 113 Nm, measures $22 \times 10 \times 5$ cm^3, and weighs 1.1 kg, excluding the battery pack [11]. When installed in a SCKAFO, the knee brace system typically weighs 3.1 kg. Many users found the orthosis to be heavy, difficult to don and doff, and cosmetically unappealing compared with their conventional KAFO [12–13]. Otto Bock released a commercial version of the DKBS in 2007, marketed as "The Sensor Walk." The Sensor Walk is the most expensive SCKAFO, selling for US$8,500 for the joint, electronics, and central-fabricated laminated orthosis.

Ottawalk Belt-Clamping Knee Joint

Yakimovich et al. developed a friction-based belt-clamping mechanism to provide free knee motion during swing in a SCKAFO knee joint [14]. During stance, the joint resists knee flexion and allows the knee to extend freely at any knee angle [14]. A belt that attaches to the upper and lower uprights and spans across the knee joint axis is clamped to achieve flexion resistance. As the knee moves into flexion (**Figure 6**), the tension in the belt increases. When the belt becomes taut, the belt pushes on a lever that clamps the belt. Belt-clamping is thus done with increasing tension in the belt itself. A knee extension moment at any time during stance reduces belt tension, thereby releasing the clamp to allow the belt to travel freely for knee extension. For free knee flexion and extension in swing, a plate is displaced into the path of the clamp lever to prevent belt-clamping. A pushrod activated by foot pressure or ankle angle is used for displacing the switch plate, thereby switching between stance and swing modes. Elasticity in the belt allows some knee flexion in early stance rather than abrupt mechanical locking. This helps absorb shock at heel strike and, potentially, smooth the path of the COM as in normal gait [30].

As with most other SCKAFOs, the knee flexion moment has to be removed to switch from stance to swing mode. As described with the Horton Stance Control Orthosis, current mechanical control methods for joint control are limited.

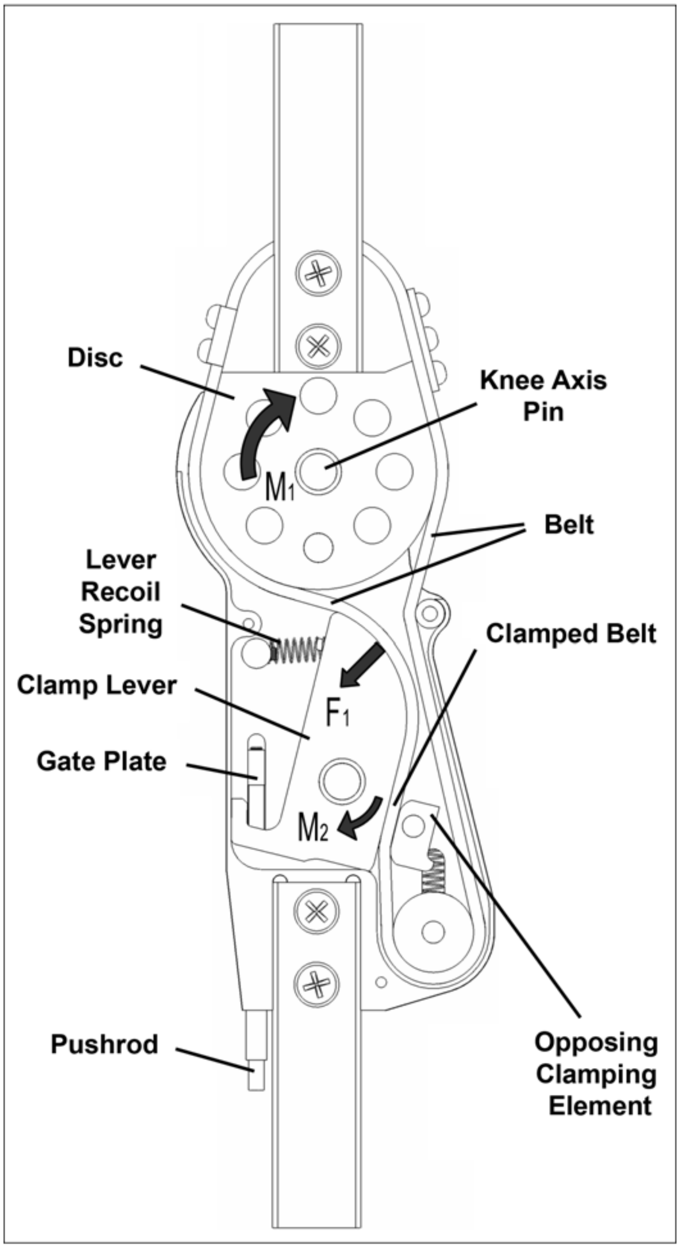

Figure 6.
Friction-based Ottawalk belt-clamping knee joint in stance mode with applied flexion moment. F_1 = belt force on clamp lever, M_1 = knee moment, M_2 = clamp lever moment.

Dual Stiffness Knee Joint

Moreno et al. have developed a SCKAFO that expands on earlier use of springs at the knee joint [31–32] by offering two levels of torsional elasticity at the knee. To detect stance and swing phases for the braced limb, gyroscopes and dual-axis accelerometers are positioned on the foot and shank, and an angular position sensor is located at the knee. The joint uses two stainless steel compression springs of stiffness K_1 and K_2, where $K_1 \gg K_2$, to achieve two levels of torsional stiffness. During stance, the device uses stiffness K_1 in the knee joint for shock absorption during initial weight-bearing and for energy return during knee extension. During swing, the device switches to stiffness K_2 to store and recover spring energy that assists knee extension in terminal swing. The SCKAFO is bulky and, because of the solenoid power requirements, has an approximately 2.5 h battery life. However, the orthosis can be modified for mechanical control by pulling on a cable during ankle dorsiflexion. This dual-spring joint is not yet commercially available.

DISCUSSION

Design Achievements

The main functions of an ideal SCKAFO are to (1) resist flexion in stance while allowing free knee extension and (2) permit free knee rotation in flexion and extension when the braced leg is unloaded in swing. While all the reviewed SCKAFO designs satisfy at least one of these requirements, some design approaches incorporated additional functional features that were advantageous. These functional features included—

1. Locking the knee or resisting knee flexion at any knee angle rather than just at full knee extension.
2. Locking the knee or resisting knee flexion at any knee or ankle angle (to ascend or descend stairs, to stand with a flexed knee, and to stabilize after stumbling).
3. Unlocking the knee at any knee or ankle angle when the braced limb is unloaded (to permit sitting and stair ascent and descent).
4. Permitting controlled knee flexion during stance (for smooth progression of the body COM and shock absorption).
5. Smoothly switching between stance and swing modes.
6. Assisting knee-extension during stance.
7. Switching stance-swing mode without requiring knee extension moment to unload the joint.

Research to date has demonstrated that SCKAFOs promote a more symmetric gait and increase mobility [3], improve gait kinematics [3,6,8,28,30,33], require less compensatory movement [3,8,30,33], and require less energy expenditure during gait [6,10,33] than conventional locked-knee KAFOs. Larger sample-sized biomechanical evaluations remain to be completed on all new experimental and commercial SCKAFOs except the DKBS [28].

For many studies, the SCKAFO accommodation period may not have been long enough to overcome the learned walking strategies for conventional KAFO or nondisabled walking. Accommodation periods of at least 3 months should be considered in future SCKAFO studies to more accurately gauge effectiveness [13]. A considerable portion of the population who use conventional KAFOs has sufficient lower-limb muscle strength to benefit from a functional KAFO, including the older population.

Several different SCKAFO designs are currently being marketed. However, all designs fall short of providing the user with completely stable and/or practical orthoses, as summarized in the **Table**.

Remaining Issues and Future Directions

SCKAFO designs should ideally incorporate all the functional features just discussed. Limitations of current devices have been partly due to inclusion of only a small subset of these features. Several current SCKAFOs require the knee to be fully extended to engage the knee joint lock and, therefore, do not support body weight during stumbling, flexed-knee standing, and stair ascent and descent.

Size, weight, and noise will always be among the most important design factors in determining if a SCKAFO is accepted and widely used by orthosis wearers. A functional and cosmetically appealing orthosis must have knee-joint components with minimal dimensions. This is most critical mediolaterally, but also important anteroposteriorly, because orthoses are commonly worn under clothing. Minimal dimensions also help minimize device weight. Several SCKAFO designs are too heavy and bulky for many potential users. These users may find the orthoses energy exhaustive, intimidating, obstructive, and awkward. People using these orthoses are thereby limited in where they can safely walk, and in some cases, they may abandon the device.

The large forces generated when resisting stance knee flexion are often directed onto relatively small locking areas within a SCKAFO knee joint. The combination of high forces distributed over a relatively small area causes very high stress in the joint's internal components. To prevent failure of these highly-stressed internal parts, the components are generally made larger, leading to a heavier and bulkier SCKAFO joint. To achieve a truly light and compact SCKAFO joint, designers must apply an innovative means of distributing force and reducing stresses throughout the joint mechanism. The use of high strength-to-weight materials could lessen the need to reduce stresses; however, the higher cost may be prohibitive.

Knee flexion at initial foot contact and early stance has not been incorporated into most SCKAFO designs. Flexion resistance has typically involved a rigidly locking mechanism. Knee flexion during stance may be of secondary importance to the challenge of achieving both flexion resistance during stance and free knee motion during swing with acceptable cosmesis.

Knee-extension assist is difficult to include in a compact design [32]. The potential risks associated with a spring-loaded device should be considered based on the high loads that would be involved to provide knee-extension support during walking, especially for adults.

Table.
Summary of characteristics of commercial stance-control knee-ankle-foot orthosis (SCKAFO) designs.

Model	Advantages	Disadvantages	Max User Weight (kg)	Approximate Cost (Can$)
Otto Bock Free Walk/Becker Orthopedic UTX	Lightweight	Locks only in full knee extension	120	$2,500 (SCKAFO)
Horton Stance Control Orthosis	Good functionality	Bulky	90	$1,350 (joints)
Fillauer Swing Phase Lock	Lightweight, autonomous	Locks only in full knee extension	Unspecified	$1,880 (joints)
Becker Orthopedic 9001 E-Knee	Good functionality	Bulky, heavy, noisy, expensive	100	$4,400 (joints, control system & uprights)
Otto Bock Sensor Walk	Good functionality, unlocks under load	Bulky, heavy, noisy, expensive	136	US$8,500 (joints, electronics, laminate orthosis)

Max = maximum.

Attaining a smooth transition between stance and swing remains a considerable challenge. Except for the DKBS, all SCKAFOs discussed in this article require a slight knee-extension moment to eliminate the net knee-flexion moment at the joint before the locking or braking mechanism is released. While this knee extension requirement alters the transition from stance to swing, the need to unload the locking mechanism before release results in a safer locomotor environment.

Designs that avoid metal-to-metal bearing and designs that apply spatially continuous forces (as in plates and belts) may be less prone to excessive noise compared with stepped ratchets, pawls, and pins, where most of the forces are borne by metal surfaces having a small area.

Current electronic control systems require a heavy, obtrusive battery that detracts from the orthosis' cosmetic and functional appeal. Effectively optimizing the control system's power consumption, combined with continually advancing battery technology, may lead to smaller control systems in the near future. In future reports, the battery and control electronics packaging should be included when device weight and dimensions are described.

SCKAFOs are a relatively new product in the orthotics industry, and many insurance plans do not recognize the technology or reimburse clients. A pair of conventional KAFO knee joints costs between Can$150 and Can$300. The cost of a pair of commercial SCKAFO joints begins at Can$1,350. When the costs of material and labor to integrate the joints into a KAFO are added, the total cost of a SCKAFO is too expensive for many potential users.

New technologies can be developed to improve current SCKAFO devices. The use of sensors to adaptively control joint stiffness is an exciting direction for lower-limb orthoses [31]. The use of actuators in lower-limb orthoses present new capabilities for adaptive control [31,34–35]. Incorporating such devices into SCKAFOs without increasing bulk and weight to the orthosis remains a challenge. The use of sensors to monitor dynamic walking stability during gait may offer potential adaptation of SCKAFOs and other lower-limb orthoses in future designs [36]. Creating a SCKAFO that addresses the limitations of current commercial designs will undoubtedly expand the potential SCKAFO user population, reduce the chance of device rejection, and improve levels of mobility, security, confidence, independence, and health of consumers with lower-limb weakness.

CONCLUSIONS

SCKAFOs have been designed to resist knee flexion in weight-bearing while allowing free knee extension and to permit free knee rotation in flexion and extension when the braced leg is unloaded. Success has been limited by the need to resist high knee moments while maintaining a compact, lightweight, and low-cost device. Designs that require knee extension to achieve knee locking and, more generally, those that are activated by the ankle or knee at specified angles limit functionality for standing, stair climbing, and recovery from stumbling. Controlled knee flexion during stance, knee-extension assistance, and smooth switching between stance and swing modes remain challenges for future designs.

ACKNOWLEDGMENTS

Author Contributions:
Study concept and design: E.D. Lemaire, T. Yakimovich, J. Kofman.
Acquisition of data: E.D. Lemaire, T. Yakimovich, J. Kofman.
Analysis and interpretation of data: E.D. Lemaire, T. Yakimovich, J. Kofman.
Drafting of manuscript: E.D. Lemaire, T. Yakimovich, J. Kofman.
Critical revision of manuscript for important intellectual content: E.D. Lemaire, T. Yakimovich, J. Kofman.
Obtained funding: E.D. Lemaire, J. Kofman.
Administrative, technical, or material support: E.D. Lemaire, J. Kofman.
Study supervision: E.D. Lemaire, J. Kofman.
Financial Disclosures: The authors have declared that no competing interests exist. No author had any paid consultancy or any other conflict of interest with this article.
Funding/Support: This material was based on work supported by the Canadian Institutes of Health Research (grant 78755) and the Natural Sciences and Engineering Research Council of Canada (grant 320180-04).

REFERENCES

1. Benson V, Marano MA, National Center for Health Statistics (U.S.), National Center for Health Statistics (U.S.) Division of Health Interview Statistics. Current estimates from the National Health Interview survey, 1992. Hyattsville (MD): U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control, National Center for Health Statistics; 1994.
2. Bowker P, Condie DN, Bader DL, Pratt DJ. Biomechanical basis of orthotic management. Oxford (UK): Butterworth-Heinemann; 1993.
3. McMillan AG, Kendrick KK, Michael JW, Aronson J, Horton GW. Preliminary evidence for effectiveness of a

stance control orthosis. J Prosthet Orthot. 2004;16:6–13. DOI:10.1097/00008526-200401000-00004
4. Waters RL, Campbell J, Thomas L, Hugos L, Davis P. Energy cost of walking in lower extremity plaster casts. J Bone Joint Surg. 1982;64:896–99. [PMID: 7085717]
5. Allard PL, Duhaime M, Thiry PS, Drown G. Use of gait stimulation in the evaluation of a spring-loaded knee joint orthosis for Duchenne muscular dystrophy patients. Med Biol Eng Comput. 1981;19:165–70. [PMID: 7266095] DOI:10.1007/BF02442710
6. Kaufman KR, Irby SE, Mathewson J, Wirta RW, Sutherland DH. Energy-efficient knee-ankle-foot orthosis: A case study. J Prosthet Orthot. 1996;8(3):79–85. DOI:10.1097/00008526-199600830-00003
7. Michael JW. Prosthetic primer: Prosthetic knees. InMotion. 1999;9:29–31.
8. Hebert JS, Liggins AB. Gait evaluation of an automatic stance-control knee orthosis in a patient with postpoliomyelitis. Arch Phys Med Rehabil. 2005;86:1676–80. [PMID: 16084826] DOI:10.1016/j.apmr.2004.12.024
9. Zissimopoulos A, Fatone S, Gard SA. Biomechanical and energetic effects of a stance-control orthotic knee joint. J Rehabil Res Dev. 2007;44(4):503–14. [PMID: 18247247] DOI:10.1682/JRRD.2006.09.0124
10. Lehmann JF, Stonebridge JB. Knee lock device for knee ankle orthoses for spinal cord injured patients: An evaluation. Arch Phys Med Rehabil. 1978;59(5):207–22. [PMID: 655831]
11. Irby SE, Bernhardt KA, Kaufman KR. Gait of stance control orthosis users: The dynamic knee brace system. Prosthet Orthot Int. 2005;29(3):269–82. [PMID: 16466156] DOI:10.1080/03093640500238915
12. Bernhardt KA, Irby SE, Kaufman KR. Consumer opinions of a stance control knee orthosis. Prosthet Orthot Int. 2006; 30(3):246–56. [PMID: 17162515] DOI:10.1080/03093640600618818
13. Irby SE, Bernhardt KA, Kaufman KR. Gait changes over time in stance control orthosis users. Prosthet Orthot Int. 2007;31(4):353–61. [PMID: 17852777] DOI:10.1080/03093640601076909
14. Yakimovich T, Kofman J, Lemaire ED. Design and evaluation of a stance-control knee-ankle-foot orthosis knee joint. IEEE Trans Neural Syst Rehabil Eng. 2006;14(3): 361–69. [PMID: 17009496] DOI:10.1109/TNSRE.2006.881578
15. Winter D. The biomechanics and motor control of human gait: Normal, elderly and pathological. Waterloo (Canada): University of Waterloo Press; 1991.
16. Marovich GD, Riley PO, Krebs DE, Mann RW, Hodge WA. Biomechanical analysis of knee motion upon stair ascent and descent. In: Proceedings of the 13th Annual Meeting of the American Society of Biomechanics; 1989; Burlington, Vermont. p. 116–17.
17. Van Leerdam NG. The swinging UTX orthosis, biomedical fundamentals and conceptual design [thesis]. Enschede (the Netherlands): University of Twente; 1993.
18. Van Leederdam NG, Kunst EE. New UTX-swing orthosis: Normal gait and safe standing. Orthopadie Technik. 1999; 50:506–15. Dutch.
19. Hatton BJ, Hatton DL, Wallace ZG, inventors. 2003. Articulating knee supports. United States patent US 6635024. 2003 Oct 21.
20. NASA Commercial Technology Division. Quicker rehabilitation for new knee brace wearers. Aerospace technology innovation. Washington (DC): National Aeronautics and Space Administration; 1997. p. 5.
21. Hatton BJ, Hatton DL, Wallace ZG, inventors. Articulating knee supports. United States patent US 20020169402. 2001 May 14.
22. Shadoan M, Myers N. Horton's orthotic lab licensed to manufacture NASA-Designed Knee Orthosis. O&P Business News. 1998;13.
23. Nijenbanning G, Goudsmit JA, inventors. Gravity operated locking hinge. United States patent US 20030153854. 2003 Aug 14.
24. Swing phase lock manual. Chattanooga (TN): Fillauer, LLC; 2007.
25. Travolta RL. Stance control revolutionizes knee bracing. Biomechanics. 2002;10:53–62.
26. Sclater N, Chironis NP. Mechanisms and mechanical devices sourcebook. New York (NY): McGraw-Hill; 2001.
27. Naft JM, Newman WS, inventors. Orthosis knee joint. United States patent US 6517503. 2003 Feb 11.
28. Irby SE, Kaufman KR, Mathewson JW, Sutherland DH. Automatic control design for a dynamic knee-brace system. IEEE Trans Rehabil Eng. 1999;7(2):135–39. [PMID: 10391583] DOI:10.1109/86.769403
29. Irby SE, Kaufman KR, Sutherland DH. Electronically controlled long leg brace. In: Proceedings of the 1996 15th Southern Biomedical Engineering Conference; 1996 Mar 29–31; Dayton, Ohio. p. 427–30.
30. Yakimovich T, Lemaire ED, Kofman J. Preliminary kinematic evaluation of a new stance-control knee-ankle-foot orthosis. Clin Biomech (Bristol, Avon). 2006;21(10):1081–89. [PMID: 16949186] DOI:10.1016/j.clinbiomech.2006.06.008
31. Moreno JC, Brunetti F, Rocon E, Pons JL. Immediate effects of a controllable knee ankle foot orthosis for functional compensation of gait in patients with proximal leg weakness. Med Biol Eng Comput. 2008;46(1):43–53. [PMID: 17926076] DOI:10.1007/s11517-007-0267-x

32. Kofman J, Allard P, Duhaime M, Labelle H, Vanasse M. A functional knee-ankle orthosis for Duchenne Muscular Dystrophy patients using a spring-loaded knee joint mechanism. Orthopadie-Technik. 1988;36:403–7.
33. Irby SE, Kaufman KR, Wirta RW, Sutherland DH. Optimization and application of a wrap-spring clutch to a dynamic knee-ankle-foot orthosis. IEEE Trans Rehabil Eng. 1999; 7(2):130–34. [PMID: 10391582] DOI:10.1109/86.769402
34. Blaya JA, Herr H. Adaptive control of a variable-impedance ankle-foot orthosis to assist drop-foot gait. IEEE Trans Neural Syst Rehabil Eng. 2004;12(1):24–31. [PMID: 15068184] DOI:10.1109/TNSRE.2003.823266
35. Ferris DP, Gordon KE, Sawicki GS, Peethambaran A. An improved powered ankle foot orthosis using proportional myoelectric control. Gait Posture. 2006;23(4):425–28. [PMID: 16098749] DOI:10.1016/j.gaitpost.2005.05.004
36. Biswas A, Lemaire ED, Kofman J. Dynamic gait stability index based on plantar pressures and fuzzy logic. J Biomech. 2008;41(7):1574–81. [PMID: 18395211] DOI:10.1016/j.jbiomech.2008.02.009

Submitted for publication February 21, 2008. Accepted in revised form August 4, 2008.