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# Hybrid Orthosis: The Technology for Spinal Cord Injury

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**Abstract:** Hybrid orthosis combined Functional Electrical Stimulation (FES) with a lower limb orthotic brace. The first hybrid orthosis system is introduce in 1972 and since many researchers began to produced hybrid orthosis from complex research devices to nearly commercialized products. The purpose of this study is to provide a review of hybrid orthosis available for rehabilitation of paraplegics. This review should provide a guide to biomedical engineers to understand the tools developed the design characteristics, the advantages and disadvantages of hybrid orthosis that strive to improve paraplegic mobility especially in walking.

**Key words:** Hybrid orthosis, paraplegic, walking, FES

## INTRODUCTION

Paraplegic is impairment in motor and/or sensory function of the lower extremities. It is usually the result of Spinal Cord Injury (SCI) which affects the neural elements of the spinal canal. Sisto *et al.* (2008) reported that more than 200,000 people in the United States (US) suffer from SCI and each year 10,000 new cases occur. Brown-Triolo *et al.* (1997); in their study found that 51% of SCI subjects defined mobility in terms of life impact and autonomy and gait was found to be perceived as the first choice in possible technology applications. Their subjects also indicated willingness to endure time intensive training and undergo surgery operation if mobility is guaranteed. Therefore, solutions to mobility loss were seen as an exciting prospect to these patients.

## HYBRID ORTHOSIS

Restoring gait in SCI is a research challenge. Researchers have investigated various electrical, mechanical and combined techniques also called hybrid orthosis to restore functional movement in the lower limbs (Ferguson *et al.*, 1999; Nene and Jennings, 1989; Nene and Patrick, 1990; Philips and Hendershot, 1991; Popovic *et al.*, 1989; Solomonow *et al.*, 1997; Tinazzi *et al*, 1997). Among the gait phases, the swing phase is important in advancing the leg in order to contribute to movement of the body in the direction of gait progress. Hip flexion is an essential part of pick-up in the swing phase of reciprocal gait, whilst passive hip extension is important during the trunk glide in stance. Researchers have attempted to provide hip flexion to improve walking by a method called Functional Electrical Stimulation (FES). For support, all FES-assisted paraplegics walking need parallel bars, walker or crutches. Moreover, paraplegic walking with only FES has significant drawbacks in function restoration. Firstly, due to stimulated muscle contractions, muscle fatigue will quickly occur because of the reversed recruitment order of the artificial stimulated motoneurons. As a result, there are limitations in standing time and walking distance. Another disadvantage is erratic stepping trajectories because of poor control of joint torque (Hausdorff and Durfee, 1991).

Hybrid systems can overcome these limitations by combining FES with the use of a lower limb orthotic brace. Orthoses can guide the limb and reduce the number of degrees of freedom in order to simplify the control problem. The use of active muscle can also be reduced by locking orthosis joints (Goldfarb *et al.*, 2003). Moreover, the approach is useful to support body weight, protect the joint and ligament (Huq, 2009). Furthermore, it rigidity improves walking efficiency and reduces overall energy cost (Stallard and Major, 1995). Several hybrid systems have been developed. The most widely tested is named Reciprocating Gait Orthosis (RGO) (Isakov *et al.*, 1992; Philips and Hendershot, 1991; Solomonow *et al.*, 1997) was designed to meet the needs of the spina bifida patient. This mechanism moves the contralateral limb forward by using surface stimulation of hip extension. Then, by alternating stimulation of the hip extensors, the walking can be achieved with less energy consumption. However, during the leg-swing phase the body requires to be lifted by the arm with the help of crutches, making it

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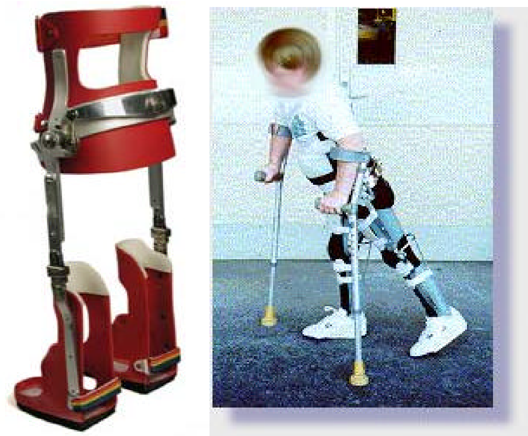

Fig. 1: Reciprocating gait orthosis

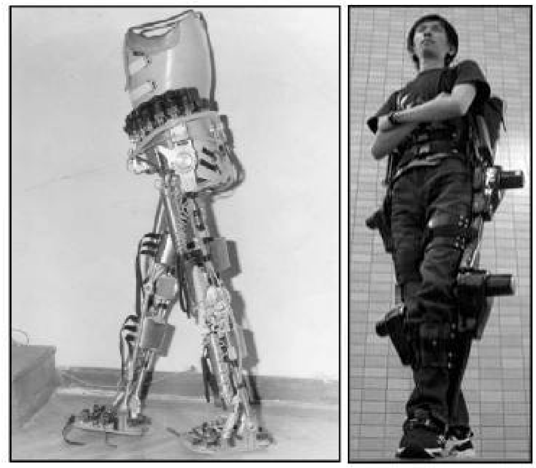

Fig. 2: Power orthosis (Ferris *et al*., 2005)

difficult to produce foot clearance. Consequently, muscle fatigue will quickly occur (Solomonow *et al*., 1997). Figure 1 shows the RGO in the market.

Another type of hybrid system is called powered orthosis used by Popovic *et al*. (1989) and Ferris *et al*. (2005) which provides more function than purely passive hybrid orthosis. A small Direct Current (DC) electric motor is installed at one or more joints with or without electrical stimulation support. A functional movement closely mimics the swing phase of gait than the flexion reflex (Popovic *et al*., 1989). However, this type of hybrid system is not used in practice because of the size and weight of motor and batteries. Figure 2 shows the power orthosis.

Goldfarb *et al*. (2003) used controlled-brake orthosis, which is able to address the constraint of FES-aided gait by combining FES with a controllable passive orthosis. This hybrid system includes computer-regulated friction brake at the hip and the knee. Muscle fatigue is reduced by locking the brakes during stance phase and turning off stimulation to the quadriceps muscle. In addition, leg movement repeats smoothly during the swing phase (Goldfarb *et al*., 2003). Figure 3 shows the controlled-brake orthosis. The size and weight also become the advantages for it user.

Kobetic *et al*. (2009) introduced their hybrid orthosis called hybrid neuroprosthesis (HNP). The system use 16 channels of FES stimulation delivered via chronically indwelling intramuscular electrodes to activate 8 different muscles for the knee, hip and ankle flexion and extension. Electrodes are connected to an External Control Unit (ECU) temporarily or permanently to an implanted generator powered and controlled via radio frequency by ECU. The Variable Constraint Hip Mechanism (VCHM) consist of hydraulic system with double acting cylinders link to each hip joint controlled by energizing specific solenoid valves was designed to maintain hip posture (Kobetic *et al*., 2009). The result obtained from the clinical test with one paraplegic subject is promising. However the system size and weight the advantages for it user.

Durfee and Rivard (2005) introduced Energy Storage Orthosis (ESO) which can be driven through a complete gait cycle. This mechanism uses stimulated muscle power to move the limb and also to drive the orthosis structure, storing energy in the process. Gas springs crossing the hip and knee joints are flexed equilibrium energy-storage elements. The energy store and transfer systems comprise a pneumatic fluid power system connected between knee and hip joints. This can capture the excess energy during the quadriceps stimulation in order to transfer to the hip and release at appropriate instant to achieve hip extension (Durfee and Rivard, 2005). Figure 4 shows the bench model of energy storage orthosis developed by Durfee and Rivard which consists gas spring on the back side.

A hybrid FES gait system concept called Spring-Brake-Orthosis (SBO) which combines mechanical braces (with coordinated joint locking mechanism) with an energy storage element mounted on it and FES to generate the swing phase of paraplegic gait is discussed further by Gharooni *et al*. (2001). This approach also substantially simplifies and reduces the problem of control tasks in a hybrid orthosis while offering more benefits on quality of a swinging leg. Previous work, Gharooni *et al*. (2001) has developed and validate SBO for leg swing phase while Huq (2009) used SBO in body weight supported treadmill locomotion in simulation environment. Then, the application of SBO is widen where it is used for paraplegic walking with wheel walker

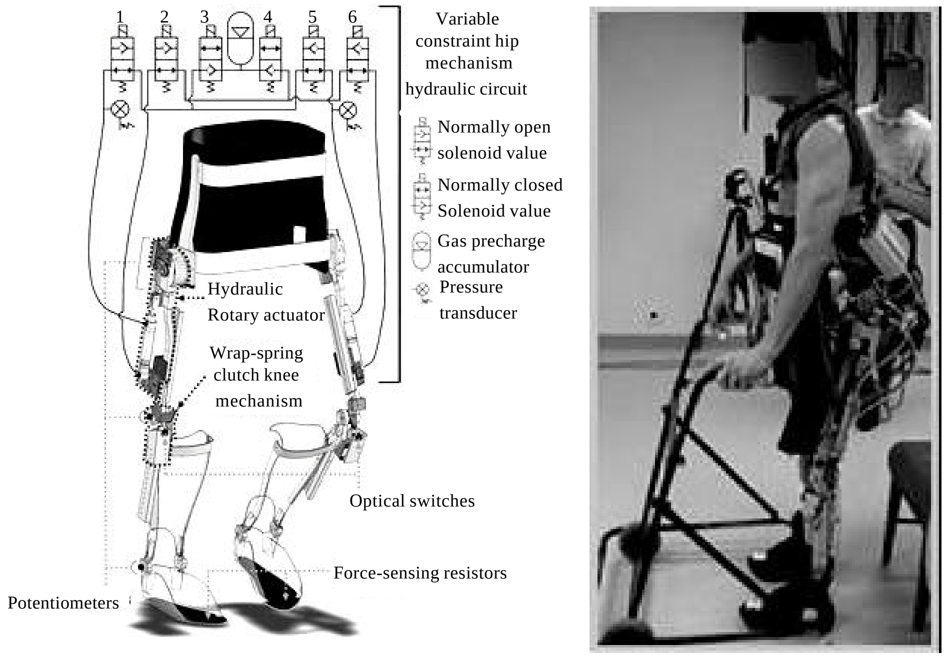


Fig. 3: Controlled-Brake Orthosis (Kobetic *et al*., 2009)

Fig. 4: Bench model physical prototype of energy storage orthosis (Durfee and Rivard, 2005)

(Jailani *et al*., 2010). The new concept in hybrid orthotics provides solutions to the problems that affect current hybrid orthosis, including knee and hip flexion without relying on the withdrawal reflex or a powered actuator and foot-ground clearance without extra upper body effort.

## WALKING GAIT IN SBO

**Knee flexion leads to hip flexion:** There are two major forces that act during walking particularly the swing phase; gravity and segment interaction forces. Gravity acts on all masses comprising the body and for the purpose of analysis, they can all be replaced with a single resultant force acting at the point of centre of mass (CoM). The projection of the centre of mass on the ground is called centre of gravity (CoG). In the SBO the spring acts as an external force on the knee joint and causes the knee to flex and potential energy is stored in the lower leg (by raising the CoM). Consequently, this causes firstly the shank to accelerate and secondly change in relative angle between the shank and thigh, with the lower extremity taking a new configuration. Both of these produce moments about the hip joint as will be illustrated in the following sections.

**Segment interaction:** In the movement of a multiple link mechanical structure such as the arm/forearm system, the torques at the joints arise not only from muscles acting on the joints but also from interactions due to movement of other links. These interaction torques are not present during movement at only a single joint and

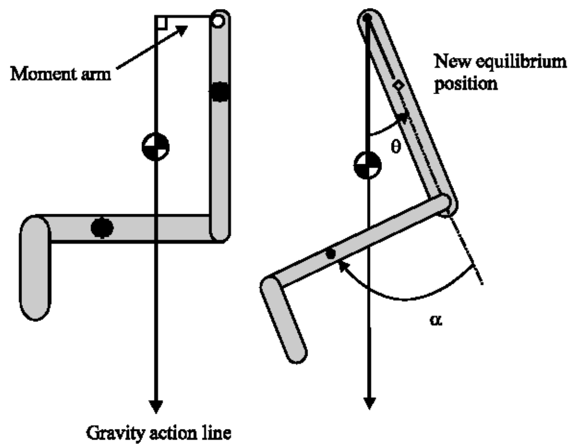


Fig. 5: Hip flexion resulting from flexed knee

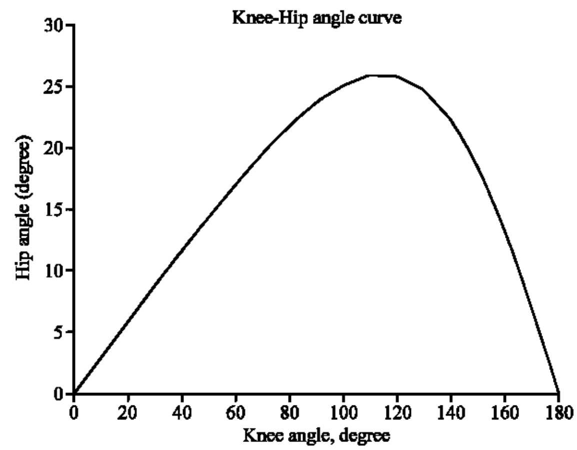


Fig. 6: Static relation between knee and hip flexion angle

represent a significantly complicated function in the dynamic analysis of movement (Hollerbach and Flash, 1982).

**Hip flexion kinetics:** During normal gait, flexion and extension of the hip and knee are linked by bi-articular muscles such as the rectus femoris and the hamstrings group, as well as kinematically and kinetically. Normal gait is initiated by hip flexion with little muscular action around the knee; the inertial properties of the shank cause the knee to flex in response to the accelerating thigh, producing ground clearance (Inman *et al*., 1981). Additionally, as the hip flexes the shank remains in the lowest potential energy position and this leads to additional knee flexion.

These inter-segment linkages also apply when knee flexion occurs without muscular activity at the hip. If the knee is flexed the action of the accelerating shank will cause the hip to flex; additionally, the new orientation of the knee will cause the leg to adopt a new minimum energy configuration with a flexed hip as illustrated in Fig. 5 and 6. The static relationship between the knee angle ($\alpha$) and hip angle ($\theta$) (Gharooni *et al*., 2001) based on anthropometric data used from Winter (1990) is given as:

$$\tan\theta = \sin\alpha/(2.426+\cos\alpha) \qquad (1)$$

This relationship is plotted in Fig. 6, which represents an ideal situation and assumes no spasticity or muscle contracture. Additional hip flexion is produced by the dynamic inter segment coupling and is dependent on the angular acceleration of the knee. Thus, it can be seen that if the knee can be made to flex by any means then this will also lead to hip flexion. The amount of hip flexion produced by the dynamic inter segment coupling is dependent on the angular acceleration of the knee. Figure 7 shows the natural hip flexion produced during knee flexion in SBO prototype developed in this thesis. These situations agree the theory explained in this section.

As indicated earlier, the swing phase is important in advancing the leg and hence movement of the body in the direction of gait progress. During pick-up, hip flexion, knee flexion and ankle dorsiflexion all combine to clear the toe. In this study it is shown that hip flexion can be produced by the knee flexion. Therefore, the only important issue in generating the swing phase is how to produce proper knee flexion. In normal and some FES-assisted walking gait, knee flexion is produced by knee flexor muscle groups such as hamstring. There are two conventional options for producing this knee flexion; direct stimulation of hamstring and use of power actuator. It is possible to directly flex the knee by means of hamstrings stimulation. Disadvantages of this technique are that the hamstrings constitute a biarticular muscle-group which constitutes extending action at the hip and limiting any resulting hip flexion, hamstrings muscle also is a weak muscle which easily tends to fatigue. The knee may also be flexed through the use of a powered-actuator such as a DC motor. To minimise inertial properties, it should be mounted away from the knee, as proximal as possible. The previously mentioned disadvantages of size and weight apply.

The stimulated quadriceps muscles group can usually produce much more torque than is required to extend the leg, even with the thigh horizontal. In SBO, 1 spring acts to resist knee extension, then the additional quadriceps torque can be used to ‘charge’ (store potential energy in) the spring when the leg is extended. A brake can then be

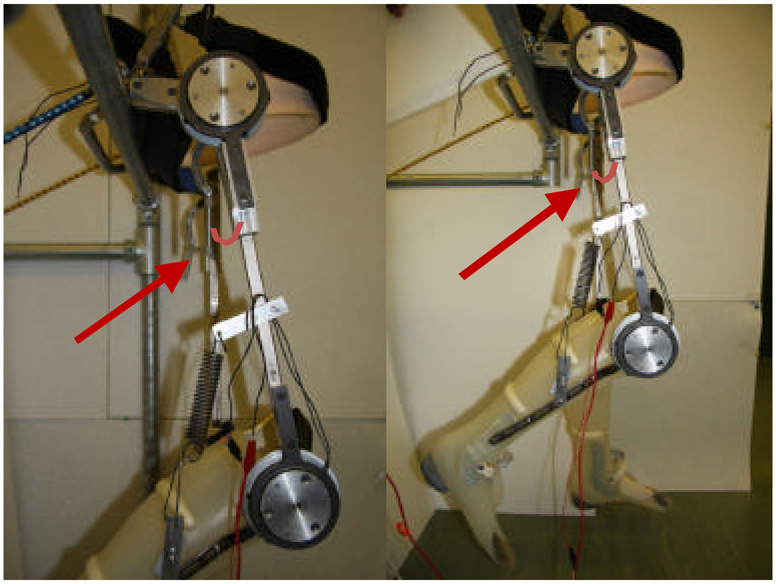

Fig. 7: Hip flexion angle produced in the knee flexion

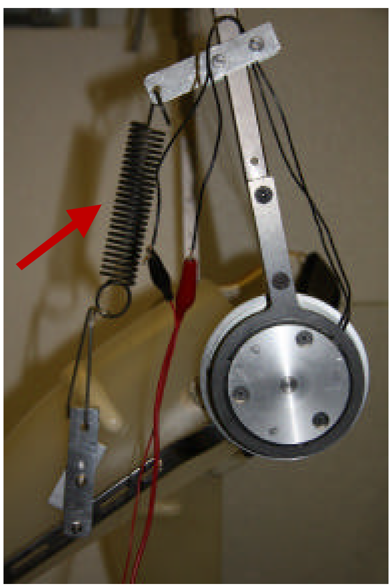

Fig. 8: Spring for knee flexion in SBO

used to maintain the knee in extension without further quadriceps contraction, preventing fatigue. When the brake is released the spring will contract, releasing its potential energy as kinetic energy and causing the knee to flex. The advantage of this approach over the use of a powered actuator is that a spring has a very high torque to weight and size ratio, efficient, robust and does not require any control signals or electrical power. Figure 8 shows the spring for knee flexion used in SBO developed.

In order to prevent the dynamic hip flexion produced by the accelerating knee from being lost, a means of 'catching' the hip at its maximum flexion angle is required. This can be achieved by using a ratchet/brake at the hip. This leads to an orthosis combining a ratchet at the hip with a brake and spring at the knee and electrical stimulation of the quadriceps.

**The swing phase SBO:** Figure 9 demonstrates the swinging leg in the SBO. To synthesise the swing phase of gait using the SBO, the following procedure is required:

- At the beginning the knee brake is on to provide isometric torque against the spring to keep the leg in stance phase (Fig. 9a)
- The brake at the knee is released and the spring causes the knee to begin to flex (Fig. 9b). It should be noticed that in practice the toe will interfere with the ground at the initiation of swing and may prevent knee flexion. This problem can be overcome by allowing the unloaded foot to dorsiflex, thus allowing the toe to slide along the ground
- Following toe-off, the spring torque will continue to accelerate the shank backwards, producing a reaction at the knee, which accelerates the thigh forwards
- The combination of the reaction and the moment due to the weight of the flexed shank cause the hip to continue to flex, the flexed knee allows the toe to clear the ground (Fig. 9b)
- While the hip reaches its maximum flexion angle, the hip ratchet keeps it in peak angle (Fig. 9b)

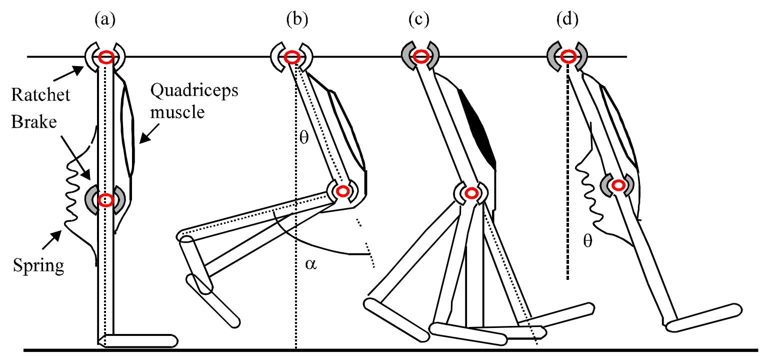


Fig. 9: SBO swing phase synthesis

- The quadriceps muscle is then stimulated to extend the knee against the spring torque (Fig. 9c)
- When the knee is fully extended the brake at the knee is applied and quadriceps stimulation is turned off (Fig. 9d)

It can be seen that it is possible to obtain knee flexion, knee extension and hip flexion using only a single channel of stimulation per leg.

## THE DEVELOPMENT OF SBO

**Brakes:** The controlled brake is the main part in those types of hybrid orthoses which use the brake as a dissipative element. Considerations for selecting a brake technology include peak resistive torque, control bandwidth, size, weight and residual friction. Most brakes are primarily designed for high angular velocity and low torque. Human gait however consists of relatively low angular velocity and high torque motion. Therefore, utilising the full range of mechanical power of the brakes requires a mechanical transmission. The transmission ratio, N must provide at least N:1 speed reduction from the brake to the joint to result in the specified maximum joint torque from the specified brake. Also the transmission ratio, N should not be too high so as not to reflect the friction and inertia from the brake to the joint. Therefore, one parameter in selecting a brake is low free rotation friction and low inertia.

There are varieties of technologies for controlled brakes in hybrid orthoses. Among these two different types of brakes, namely, wrap-spring clutch and magnetic particle brake have been reported by some researchers in hybrid orthosis design. Irby and colleagues (Irby *et al*., 2007) have suggested using a wrap-spring clutch within a Knee-Ankle Foot Arthosis (KAFO) system. The wrap-spring clutch is a principle that is proven in transmission of rotational movement. The effects of friction when a flexible body is surrounding a non-movable body are amplified in an exponential manner; thus, a small force at one end can hold a large force at the other end. This design allows device minimisation and overall reduction in energy consumption when compared with other brake systems used in orthotics. Durfee and Hausdorff (1990) reported the use of magnetic particle brake in the CBO. It was shown in their report that magnetic particle brake as a controllable mechanical damping element at the joint with combined stimulation provides good control of limb motion despite variations in muscle properties (Durfee and Hausdorff, 1990).

Fortunately, the kinematics of the SBO reduces the complexity of brake dynamics. In the SBO, brake torque is applied to oppose the isometric torque of the spring. As described in the previous section, the brake should be on when the knee joint reaches its maximum extension. In this case the angular velocity is zero, therefore the brake only needs to provide a *static* torque equal and opposite to the spring torque. This point simplifies the issues related to the selection and design of a brake further, as the dynamic characteristics of the brake do not need to be accounted for.

**Maximum brake torques:** Since power flow is from the joint to the brake, the brake in any circumstance should be capable of producing the maximum resistive torque required on the joint flexion and extension range of motion. Maximum joint torque specification of the orthosis joint depends upon three desired capabilities:

- The orthosis should be able to provide the dissipative torque observed in normal gait. Maximum dissipative torque for knee and hip are approximately 0.4 Nm $kg^{-1}$ for knee and 0.3 Nm $kg^{-1}$ for hip (Winter, 1990). For a body of 80 kg, the maximum dissipative knee and hip torque are 32 Nm and 24 Nm


Fig. 10: (a) Brake used in SBO and (b) Brake for knee and hip in SBO

- The orthosis must be capable of locking a joint against a stimulated muscle contraction. The strength of electrically stimulated knee extensors (quadriceps muscle) was studied by Baid and Kralj (Bajd *et al*, 1995) in some groups of paraplegic subjects. According to their experience knee joint torque over 50 Nm permits the performance of functional FES activities, such as standing up and reciprocal walking
- The orthosis should be able to perform controlled stand-to-sit manoeuvre without the help of muscle stimulation

Based on the above, Goldfarb and Durfee (1996) selected maximal braking loads of 50 Nm for the knee and 30 Nm for the hip joint. However, in the case of SBO as the knee brake is resisting the spring torque and not the muscle torque, the minimum braking load is reduced to 10 Nm, which is the spring torque exerted on the knee joint.

Also in selecting the brake it is important to consider those types of brakes which provide high torque with minimum input power for minimum size and weight. The wrapped spring clutches among other types of brakes offer high torque in a small package size and low power consumption for their torque capability when compared with typical friction clutches and brakes. Figure 10a and b show the brake that has been chosen in this thesis for SBO development. In this SBO, as the knee reaches full extension position the brake is turned on at the knee joint by push button switch.

## CONCLUSIONS

This review identified the application and uses of hybrid technologies that have impacts for the SCI mobility. The outcome of hybrid orthosis assisted mobility mechanism and associated aspects that influence their use by SCI and their limiting factors were discussed. Providing assistive technologies that fit well and are cosmetically appealing, environmentally friendly and cost effective is challenge that most rehabilitation engineers are facing today. More research and development in this area is essential to improve the quality of life of SCI individuals.

The hybrid orthosis can be modified, either mechanically or electronically and can be integrated with FES to assist the SCI person in obtaining upright perpendicularly loaded position for bipedal locomotion. The FES technology has growth significantly over the past ten years but still the extensive use of FES application for rehabilitation and SCI mobility is limited. Therefore, hybrid orthosis become promising device to be used with FES and more research and development in this area is motivating.

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