IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE)
ISSN(e) : 2278-1684, ISSN(p) : 2320–334X, PP : 26-31
www.iosrjournals.org

Reducing the Energy Cost of Human Walking Using an Unpowered Exoskeleton

Shrinivas G. Nagekar[1], Stephen K. Pereira[2], Mohammed Yaseen[3*]
Guide:Prof.Poojesh C. Anvekar
1,2,3Student, Dept. of Mechanical Engineering, Girijabai Sail Institute of Technology, Karwar, India

Abstract: *As one of the most important examples of human-oriented system, theexoskeleton can improve the strength and endurance of the wearer. With the recent advancements in technology, wearable devices or exoskeletons witness intense development. Passive unpowered exoskeletons are starting to emerge that have advantages compared to the powered solutions; simpler design, lower weight, no complex electronics and lower price. Such an exoskeleton has a higher chance of end-user acceptance. Metabolic energy used during walking can be partly replaced by power input from an exoskeleton. We built a lightweight elastic device that acts in parallel with the user's calf muscles, off-loading muscle force and thereby reducing the metabolic energy consumed in contractions. Results show that by choosing a proper spring, metabolic cost reduction of walking can be achieved. Improving upon walking economy in this way is analogous to altering the structure of the body such that it is more energy-effective at walking. While strong natural pressures have already shaped human locomotion, improvements in efficiency are still possible.*

Keywords: *exoskeleton, walking, unpowered, mechanics, springs, metabolic cost*

I. Introduction

With efficiencies derived from evolution, growth and learning, humans are very well-tuned for locomotion. Metabolic energy used during walking can be partly replaced by power input from an exoskeleton, but is it possible to reduce metabolic rate without providing an additional energy source? This would require an improvement in the efficiency of the human–machine system as a whole, and would be remarkable given the apparent optimality of human gait. Here we show that the metabolic rate of human walking can be reduced by an unpowered ankle exoskeleton. We built a lightweight elastic device that acts in parallel with the user's calf muscles, off-loading muscle force and thereby reducing the metabolic energy consumed in contractions. The device uses a mechanical clutch to hold a spring as it is stretched and relaxed by ankle movements when the foot is on the ground, helping to fulfil one function of the calf muscles and Achilles tendon. Unlike muscles, however, the clutch sustains force passively. The exoskeleton consumes no chemical or electrical energy and delivers no net positive mechanical work, yet reduces the metabolic cost of walking by 7.2 ±2.6% for healthy human users under natural conditions, comparable to savings with powered devices. Improving upon walking economy in this way is analogous to altering the structure of the body such that it is more energy-effective at walking. While strong natural pressures have already shaped human locomotion, improvements in efficiency are still possible. Much remains to be learned about this seemingly simple behaviour.

II. Literature Survey

"Reducing the energy cost of human walking using an unpowered exoskeleton" Steven H. Collins, M. Bruce Wiggin, and Gregory S. Sawicki. PMID: 25830889, 11 June 2015. [1]

With efficiencies derived from evolution, growth and learning, humans are very well-tuned for locomotion. Metabolic energy used during walking can be partly replaced by power input from an exoskeleton, but is it possible to reduce metabolic rate without providing an additional energy source? This would require an improvement in the efficiency of the human-machine system as a whole, and would be remarkable given the apparent optimality of human gait. Here we show that the metabolic rate of human walking can be reduced by an unpowered ankle exoskeleton. We built a lightweight elastic device that acts in parallel with the user's calf muscles, off-loading muscle force and thereby reducing the metabolic energy consumed in contractions. The device uses a mechanical clutch to hold a spring as it is stretched and relaxed by ankle movements when the foot is on the ground, helping to fulfill one function of the calf muscles and Achilles tendon. Unlike muscles, however, the clutch sustains force passively. The exoskeleton consumes no chemical or electrical energy and delivers no net positive mechanical work, yet reduces the metabolic cost of walking by 7.2 ± 2.6% for healthy human users under natural conditions, comparable to savings with powered devices. Improving upon walking economy in this way is analogous to altering the structure of the body such that it is more energy-effective at walking. While strong natural pressures have already shaped human locomotion, improvements in efficiency are still possible. Much remains to be learned about this seemingly simple behavior.

"Control of lower limb exoskeleton for elderly assistance on basic mobility tasks"(D. Miranda-Linares, G. Alrezage, M.O.Tokhi ICSTCC).ISBN: 978-1-4799-8480-0, October 2015.[2]

This paper presents the modeling, simulation and control of lower limbs exoskeleton devices whose aim is to assist elderly people during standing-up and walking tasks. A humanoid and actuated exoskeleton frames were modeled in Solid Works and assembled in Visual Nastran 4D virtual environment. Control of exoskeletons actuators by means of PID and fuzzy controllers, together with a finite state machine, was designed. Simulations of the humanoid wearing an exoskeleton to perform the mentioned tasks, using controllers with set and adaptive orientation references as input, were performed. It is assumed that the humanoid, representing an old person, is only capable to provide 70% of the required torque, therefore the exoskeleton must supply 30% to complete the motions. With the aid of exoskeleton devices, the elderly will be able to perform motions of a physically able people. Optimization of fuzzy controller parameters for walking motion was done using SDA. The exoskeleton succeeded on assisting standing-up and walking motions but research is still needed to improve the performance and adaptability of the system.

"Metabolic cost adaptations during training with a soft exosuit assisting the hip joint" Fausto A. Panizzolo, Gregory M. Freisinger, Nikos Karavas, Asa M. Eckert-Erdheim, Christopher Siviy, Andrew Long, Rebecca A. Zifchock, Michael E. LaFiandra & Conor J. Walsh. Artical no: 9779(2019) 05 July 2019 ISSN 2045-2322

Different adaptation rates have been reported in studies involving ankle exoskeletons designed to reduce the metabolic cost of their wearers. This work aimed to investigate energetic adaptations occurring over multiple training sessions, while walking with a soft exosuit assisting the hip joint. The participants attended five training sessions within 20 days. They walked carrying a load of 20.4 kg for 20 minutes with the exosuit powered and five minutes with the exosuit unpowered. Percentage change in net metabolic cost between the powered and unpowered conditions improved across sessions from −6.2 ± 3.9% (session one) to −10.3 ± 4.7% (session five), indicating a significant effect associated with training. The percentage change at session three (−10.5 ± 4.5%) was similar to the percentage change at session five, indicating that two 20-minute sessions may be sufficient for users to fully adapt and maximize the metabolic benefit provided by the exoskeleton. Retention was also tested measuring the metabolic reduction five months after the last training session. The percent change in metabolic cost during this session (−10.1 ± 3.2%) was similar to the last training session, indicating that the adaptations resulting in reduced metabolic cost are preserved. These outcomes are relevant when evaluating exoskeletons' performance on naïve users, with a specific focus on hip extension assistance.

"Exoskeleton boots improve on evolution" Davide Castelvecchi 01 April 2015 ISSN 0028-0836 EISSN 1476-4687

Boots rigged with a simple spring-and-ratchet mechanism are the first devices that do not require power aids such as batteries to make walking more energy efficient.

People walking in the boots expend 7% less energy than they do walking in normal shoes, the devices' inventors report on 1 April in Nature1. That may not sound like much, but the mechanics of the human body have been shaped by millions of years of evolution, and some experts had doubted that there was room for further improvement in human locomotion, short of skating along on wheels. "It is the first paper of which I'm aware that demonstrates that a passive system can reduce energy expenditure during walking," says Michael Goldfarb, a mechanical engineer at Vanderbilt University in Nashville, Tennessee, who develops exoskeletons for aiding people with disabilities.

As early as the 1890s, inventors tried to boost the efficiency of walking by using devices such as rubber bands, says study co-author Gregory Sawicki, a biomedical engineer and locomotion physiologist at North Carolina State University in Raleigh. More recently, engineers have built unpowered exoskeletons that enable people to do tasks such as lifting heavier weights — but do not cut down the energy they expend. (Biomechanists still debate whether the running 'blades' made famous by South African sprinter Oscar Pistorius are more energetically efficient than human feet.2, 3)

"The Effects of Exoskeleton Assisted Knee Extension on Lower-Extremity Gait Kinematics, Kinetics, and Muscle Activity in Children with Cerebral Palsy" Zachary F. Lerner, Diane L. Damiano & Thomas C. Bulea Artical no: 13512 (2017) ISSN 2045-2322

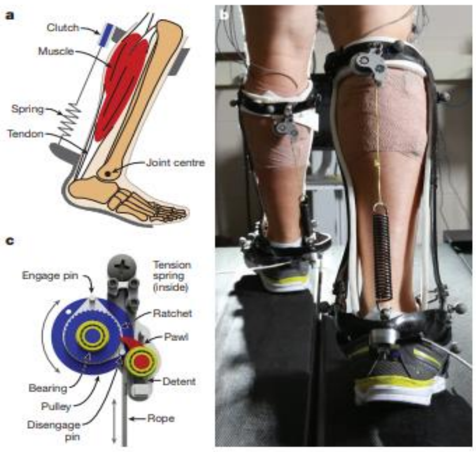
Individuals with cerebral palsy often exhibit crouch gait, a debilitating and inefficient walking pattern marked by excessive knee flexion that worsens with age. To address the need for improved treatment, we sought to evaluate if providing external knee extension assistance could reduce the excessive burden placed on the knee extensor muscles as measured by knee moments. We evaluated a novel pediatric exoskeleton designed to provide appropriately-timed extensor torque to the knee joint during walking in a multi-week exploratory clinical study. Seven individuals (5–19 years) with mild-moderate crouch gait from cerebral palsy (GMFCS I-II) completed the study. For six participants, powered knee extension assistance favorably reduced the excessive stance-phase knee extensor moment present during crouch gait by a mean of 35% in early stance and 76% in late stance. Peak stance-phase knee and hip extension increased by 12° and 8°, respectively. Knee extensor muscle activity decreased slightly during exoskeleton-assisted walking compared to baseline, while knee flexor activity was elevated in some participants. These findings support the use of wearable exoskeletons for the management of crouch gait and provide insights into their future implementation.

III. Objectives

- We attempt to construct a lower body exoskeleton that assists human locomotion. The unpowered exoskeleton consumes no chemical or electrical energy and, yet reduces the metabolic cost of walking by 7% for healthy human users under natural conditions.
- To built a lightweight elastic device that acts in parallel with the user's calf muscles, off-loading muscle force and thereby reducing the metabolic energy consumed in contractions
- This bodes well for a future with devices that are lightweight, energy-efficient, and relatively inexpensive, yet enhance human mobility.
- Metabolic energy used during walking can be partly replaced by power input from an exoskeleton, but is it possible to reduce metabolic rate without providing an additional energy source
- The metabolic rate of human walking can be reduced by an unpowered ankle exoskeleton. We built a lightweight elastic device that acts in parallel with the user's calf muscles, off-loading muscle force and thereby reducing the metabolic energy consumed in contractions.

IV. Methodology

Figure 1 | Unpowered exoskeleton design. a, The exoskeleton comprises rigid sections attached to the human shank and foot and hinged at the ankle. A passive clutch mechanism and series spring act in parallel with the calf muscles and Achilles tendon. b, Participant walking with the device. Load cells measured spring force. c, The passive clutch mechanism has no electronics, but instead uses a ratchet and pawl that mechanically engage the spring when the foot is on the ground and disengage it when the foot is in the air of the body remain constant on average. Humans expend metabolic energy during walking in part to restore energy that has been dissipated, in passive motions of soft tissues for example, but the greatest portion of waste occurs in muscles. Muscles consume metabolic energy to perform positive work, as required by conservation of energy, but they also use metabolic energy to produce force isometrically and to perform negative work. This places a metabolic cost on body weight support and on holding tendons as they stretch and recoil. By contrast, mechanical clutches require no energy to produce force. We designed a lightweight exoskeleton that provides some of the functions of the calf muscles and tendons during walking, but uses more efficient structures for those tasks. It has a spring in parallel with the Achilles tendon connected to the leg using a lightweight composite frame with a lever about the ankle joint (Fig. 1b and Extended Data Fig. 2). A mechanical clutch in parallel with the calf muscles engages the spring when the foot is on the ground and disengages it to allow free motion when the foot is in the air. This design was inspired by ultrasound imaging studies suggesting clutch like behaviour of muscle fascicles to hold the spring-like Achilles tendon, the recoil of which leads to the largest burst of positive mechanical power at any joint during walking. The exoskeleton clutch, has no motor, battery or computer control, and weighs 0.057 kg. The entire exoskeleton has a mass of between 0.408 and 0.503 kg per leg, depending on participant size. On the basis of simulation studies of walking with elastic ankles, we expected an intermediate stiffness to minimize energy cost and performed tests with a range of springs. We conducted experiments with healthy participants (N= 9) wearing an exoskeleton on each leg while walking at a normal speed (1.25 m s21) on a treadmill. The exoskeleton produced a pattern of torque similar to that produced by the biological ankle, but with lower magnitude (Fig. 2a). This reduced the ankle moment produced by calf muscles (Fig. 2b) and reduced calf muscle activation, particularly in the soleus (Fig. 2c). Joint angles changed little across conditions (Fig. 2d), confirming that the exoskeleton did not interfere with other normal ankle functions, such as toe clearance during leg swing (60–100% stride). The exoskeleton reduced human metabolic energy consumption when using moderate-stiffness springs (Fig. 3). Wearing a lightweight exoskeleton on each ankle without springs did not measurably increase energy cost compared with normal



walking. With increasing spring stiffness, metabolic rate first decreased then increased, supporting the hypothesis that an intermediate stiffness would be optimal. The 180 N m rad spring reduced the metabolic cost of walking to 2.67 ± 0.14W kg (mean± standard error), down from 2.886 0.10W kg for normal walking, a reduction of 7.2 ± 2.6% (paired t-test: P = 0.023).

Figure 2 | Mechanics and muscle activity. a, Exoskeleton torque (normalized to body mass) in time (normalized to stride period) for each spring, averaged across participants. Bars at right are the averages of these trajectories in time; N= 9, P values indicate the results of analysis of variance (ANOVA) tests for an effect of spring stiffness; NE, no exoskeleton. Exoskeleton torque increased with spring stiffness (except with the stiffest spring, which tended to be engaged later in stance). b, Time course of the biological contributions to ankle moment, which decreased with increasing spring stiffness. c, Time course of electrical activity in the soleus muscle, an ankle plantar flexor, which decreased with increasing spring stiffness. d, Time course of ankle joint angle, which triggered passive clutch engagement and disengagement. The ratchet was engaged at heel strike, took up slack through foot flat, held the spring as it stretched and recoiled through mid- and late stance, and disengaged to allow toe clearance during leg swing. The average stride period was 1.15±0.08s(mean±s.d.)

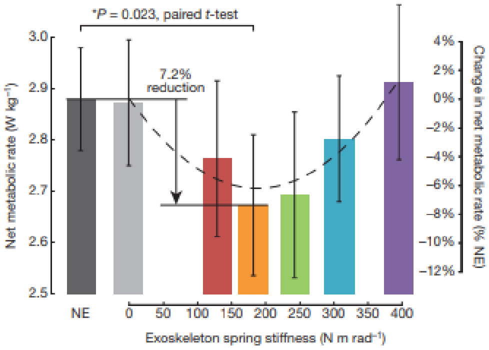
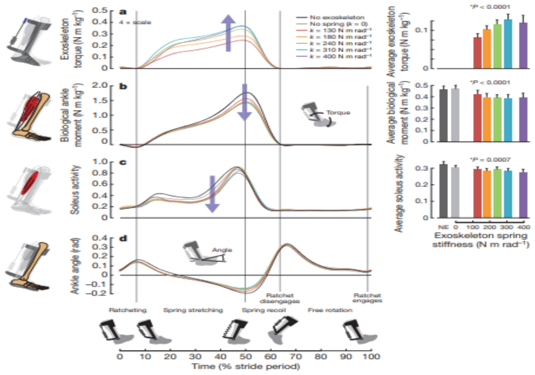


Figure 3 | Human metabolic rate. Spring stiffness affected metabolic rate (N = 9; ANOVA with second-order model; P stiffness = 0.016, Pstiffness2 = 0.008). Net metabolic rate, with the value for quiet standing subtracted out, was 7.2 ± 2.6% (mean ±s.e.m.) lower with the 180 N m rad spring (orange bar) than during normal walking (dark grey bar; paired two-sided t-test with correction for multiple comparisons; P = 0.023). The dashed line is a quadratic best fit to mean data from exoskeleton conditions (R2 = 0.91, P = 0.029). Wearing the exoskeleton with the spring removed (light grey bar, k = 0) did not increase energy cost compared with normal walking (paired t-test; P = 0.9). Error bars, s.e.m., dominated by inter-participant variability. 1.47 ± 0.1 W kg in this study. The observed reduction is similar to improvements with high-powered devices and equivalent to the effect of taking off a 4 kg backpack for an average person. It is difficult to attribute changes in whole-body metabolic rate to a particular change in muscle mechanics, but with this device there is an association with reduced muscle forces at the assisted ankle joints. Muscles consume energy whenever active, even when producing force without performing mechanical work. Simply reducing muscle force can therefore save metabolic energy. For all exoskeleton springs, we measured reductions in the biological component of ankle moment and the activity of major plantar flexor muscles, both indicative of reduced force. Reductions occurred primarily during early and mid-stance (0–40% stride, Fig. 2b, c) when muscle fascicles are nearly isometric and therefore perform little mechanical work24. Simulation models estimate that plantar flexor muscle energy use primarily occurs during this period and accounts for about 27% of the metabolic energy used for walking. With the 180 N m rad spring, the biological component of average ankle moment was reduced by 14% and mid-stance soleus electrical activity was reduced by 22% compared with normal walking.



Exoskeleton hardware. Custom frames were fabricated for each participant using modified orthotics methods. A flexible cast was used to create a positive plaster mould of the foot, ankle and shank, upon which a thin, selectively reinforced carbon fibre frame was formed. Shank and foot segments were removed from the mould and connected using an aluminium hinge joint with a plain bearing (Extended Data Fig. 2). The custom mechanical clutch (Fig. 1c and Supplementary Methods) was then integrated with the frame and a demonstration of clutch function can be found in Supplementary Video 2. We used five sets of steel coil extension springs with stiffnesses of 5.6, 7.9, 10.5, 13.3 and 17.2 kN m and masses of 0.059, 0.061, 0.068, 0.092 and 0.098 kg, respectively. Spring stiffnesses were determined in experiments where springs were stretched to several displacements using a fixture and forces were measured using a load cell. Springs were attached to a lever arm on the foot frame with an average radius of 0.152 m, resulting in average exoskeleton rotational stiffnesses of 130, 180, 240, 310 and 400 N m rad . This spans the range of reported ankle joint quasi-stiffnesses for walking. To measure force, a single-axis load cell was placed in series with the spring. Exoskeleton joint torque was calculated as the product of spring force and the lever arm, assuming constant leverage.

V. Results and Conclusions

Joint angles, moments and powers were calculated from body motions and ground reaction forces using inverse kinematics and inverse dynamics analyses (Visual 3D, C-Motion). Components of joint moment and power attributed to the human (biological component) were calculated by subtracting the exoskeleton torque or power, measured using onboard sensors, from the total ankle joint moment or power, estimated using inverse dynamics. Centre-of-mass power was calculated from ground reaction forces using the individual limbs method. Muscle activity was band-pass filtered (20–460 Hz) in hardware and then conditioned by rectifying and low-pass filtering with a cutoff frequency of 6 Hz in software. Medial and lateral gastrocnemius signals were combined to simplify analysis and interpretation. Metabolic rate was estimated from average rates of oxygen consumption (VO2) and carbon dioxide production (VCO2) during the collection window using a standard formula. The metabolic rate during quiet standing was subtracted from gross metabolic rate to obtain the net value attributable to the energetic demands of walking2,10,16,22,26. Net metabolic rate values were then normalized to participant body mass. Mechanics data and muscle activity from each condition were broken into strides, determined as the period between subsequent heel strikes of a single leg, and an average stride for each participant and condition was obtained. These average strides were used to calculate values of average moment, mechanical power and muscle activity for each participant and condition. Average moment and power values were calculated as the time integral of moment and power time series data divided by stride period. Positive and negative average joint moments and powers were separated out using time integrals of periods of positive or negative moment or power, respectively. Average net power was calculated as the time integral of power over the whole stride period. Average moment and power values were normalized to participant body mass. Average muscle activity was calculated as the time integral of muscle activity divided by stride period. Average muscle activity during additional periods of interest was calculated as the time integral of muscle activity during those periods divided by stride period (for example, early and mid-stance, defined as 0–40% stride, and late stance, defined as 40–60% stride).Muscle activity was normalized to the maximum value observed during normal walking for each muscle and for each participant. For each condition, study-wide average trajectories of lower-limb joint angles, moments and powers were calculated by averaging across participants and was measured that this unpowered exoskeleton increases metabolic rate by ± 7%.

VI. Applications and Advantages

Application:

- Health care : There is an eminent need to produce an exoskeleton device complex enough to safely assist older people in everyday activities.
- Military :Enhances strength and endurance to carry taxing loads over distance enables better handling and support for heavy weapons reduces metabolic cost of transport to improve endurance and reduce fatigue increases ability to traverse stairs, inclines, and rough terrain, especially with load reduces stress on leg muscles.
- Industrial : they are designed to detect movements initiated by their wearers to provide additional strength.

Advantages:

- Increase human walking efficiency
- Light weight
- No external power source required
- No complex mechanism
- Noiseless operation
- Easily wearable

VII. Scope for future work

It should be noted that this is only one variation of unpowered ankle exoskeleton design and that it is likely possible to achieve larger improvements in energy economy. Nonlinear springs, for example stiffening springs that have a greater ratio of change in torque to change in angle at higher torque, might provide additional benefits. Alternate engagement points, or engagement points that are altered on a step by step basis to aid balance , might also be beneficial. Coupling of exoskeleton ankle joints to knee joints might allow energy normally dissipated at the knee during late swing to be captured and used to augment ankle push-off. Different ways of attaching to the body could improve load transfer and reduce dissipation. This is a small sample of the many possible related designs that could result in improved performance. Appropriate passive assistance at other joints, particularly the hip , might provide similar benefits. In the future, we expect such devices to surpass the level of unpowered assistance set in this study. The addition of active power might lead to further improvements

References

[1]. *"Reducing the energy cost of human walking using an unpowered exoskeleton"* Steven H. Collons, M. Bruce Wiggin, and Gregory S. Sawicki. PMID: 25890889, 11 June 2015

[2]. "Control of lower limb exoskeleton for elderly assistance on basic mobility tasks" D. Miranda-Linares, G. Alrezage, M.O.Tokhi :(ICSTCC). ISBN: 978-1-4799-8480-0, October 2015

[3]. *"An Adaptive Wearable Parallel Robot for the Treatment of Ankle Injuries".* Prashant K. Jamwal, Sheng Q. Xie, *Senior Member, IEEE*, Shahid Hussain, and John G. Parsons *:* ISSN: 1941-014X, October 2012.

[4]. "Adaptive Knee Joint Exoskeleton Basedon Biological Geometries"sDonghai Wang, Kok-Meng Lee, Fellow, IEEE, Jiajie Guo, Member, IEEE, and Can-Jun Yang ISSN: 1941-014X, September 2013

[5]. "*Interactive Learning for Sensitivity Factors of a Human-Powered Augmentation Lower Exoskeleton"* Rui Huang, Hong Cheng, Senior Member, IEEE, Qiming Chen, Huu-Toan Tran, Xichuan Lin. ISBN: 978-1-4799-9993-4, Sept 28 - Oct 2, **2015.**

[6]. "Ultrasound imaging links soleus muscle neuromechanics and energetics during human walking with elastic ankle exoskeletons" R.W. Nuckols, T.J.M.Dick, O, N, Beck & G. S. Sawicki ISSN 2045-2322, 27 February 2020

[7]. "Metabolic cost adaptations during training with a soft exosuit assisting the hip joint" Fausto A. Panizzolo, Gregory M. Freisinger, Nikos Karavas, Asa M. Eckert-Erdheim, Christopher Siviy, Andrew Long, Rebecca A. Zifchock, Michael E. LaFiandra & Conor J. Walsh. Artical no: 9779(2019) 05 July 2019 ISSN 2045-2322

[8]. "Energy neutral: the human foot and ankle subsections combine to produce near zero net mechanical work during walking" Kota Z. Takahashi, Kate Worster & Dustin A. Bruening Artical no: 15404 (2017) 13 November 2017 ISSN 20450-2322

[9]. "The influence of orthosis options on walking parameters in spinal cord-injured patients" M Arazpour, M Samadain, K Ebrahimzadeh, M Ahmadi Bani & S W Hutchins.

[10]. Artical no: 412-422(2016) 09 February 2016 ISSN 1476-5624

[11]. "Exoskeleton boots improve on evolution" Davide Castelvecchi 01 April 2015

[12]. "The Effects of Exoskeleton Assisted Knee Extension on Lower-Extremity Gait Kinematics, Kinetics, and Muscle Activity in Children with Cerebral Palsy" Zachary F. Lerner, Diane L. Damiano & Thomas C. Bulea Artical no: 13512 (2017) ISSN 204