2013 IEEE/RSJ International Conference on
Intelligent Robots and Systems (IROS)
November 3-7, 2013. Tokyo, Japan

ASSISTON-KNEE: A Self-Aligning Knee Exoskeleton

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Abstract— **We present kinematics, actuation, detailed design, characterization results and initial user evaluations of ASSISTON-KNEE, a novel self-aligning active exoskeleton for robot-assisted knee rehabilitation. ASSISTON-KNEE can, not only assist flexion/extension movements of the knee joint but also accommodate its translational movements in the sagittal plane. Automatically aligning its joint axes, ASSISTON-KNEE enables an ideal match between human knee axis and the exoskeleton axis, guaranteeing ergonomy and comfort throughout the therapy. Self-aligning feature significantly shortens the setup time required to attach the patient to the exoskeleton, allowing more effective time spent on exercises. The proposed exoskeleton actively controls the rotational degree of freedom of the knee through a Bowden cable-driven series elastic actuator, while the translational movements of the knee joints are passively accommodated through use of a 3 degrees of freedom planar parallel mechanism. ASSISTON-KNEE possesses a lightweight and compact design with significantly low apparent inertia, thanks to its Bowden cable based transmission that allows remote location of the actuator and reduction unit. Furthermore, thanks to its series-elastic actuation, ASSISTON-KNEE enables high-fidelity force control and active backdriveability within its control bandwidth, while featuring passive elasticity for excitations above this bandwidth, ensuring safety and robustness throughout the whole frequency spectrum.**

I. INTRODUCTION

Electro-mechanical systems for rehabilitation are becoming ubiquitous thanks to recent advances in human machine interaction research. Robot assisted rehabilitation systems are known to be useful for delivering repetitive and physically involved rehabilitation exercises with increased intensity and accuracy. These devices are also advantageous, as they can provide quantitative measurements of patient progress. Clinical trials on robot assisted rehabilitation provide evidence that this form of therapy is effective for motor recovery and possesses high potential for improving functional independence of patients [1]–[4].

Much of research in this area has concentrated on design of highly backdriveable and/or compliant robots for safe human-robot interaction even under power losses [5]–[8] and derivation of control algorithms that assist patients only as much as needed [9]–[11], such that active involvement of patients in the therapy routine can be ensured.

Another important line of research specifically focuses on design of ergonomic exoskeleton-type rehabilitation robots. Exoskeletons are attached to human limb at multiple interaction points and movement of these devices correspond with human joints. These devices are preferred since they can apply controlled torques to targeted joints and measure decoupled movements of each joint individually. An imperative design criteria for exoskeleton-type robots is ensuring correspondence of robot axes with human joint axes. Misalignments take place since (i) human joints have complex kinematics and cannot be modeled as simple collections of kinematic pairs, (ii) the exact configuration of the human joints cannot be determined externally without utilizing special imaging equipment, and (iii) placement of the human limb with respect to the exoskeleton changes from one therapy session to another [12]–[14]. Misalignment of joint axes causes detrimental parasitic forces on the patient at the attachment points and at the joints, resulting in discomfort, pain or even long term injury under repetitive use. Most crucially, axis misalignment promotes compensatory movements that can inhibit recovery and decrease real life use of the limb due to unfavored energetics of these movements [15].

The need for exoskeletons that can comply with complex movements of human joints has been pointed out for the shoulder joint [16] and since then, several exoskeletons that can replicate or closely approximate complex shoulder joint movements have been proposed [17]–[19]. Complex joint movements at the lower limbs, especially at the knee, have received relatively less attention. Even though most prosthetics and orthotics devices, such as [20], [21], enable complex movements at the knee and allow movements of joint axis during motion, this capability has not been integrated in most of the existing rehabilitation devices. For instance, well-known lower limb exoskeletons such as Lokomat [22] and LOPES [23] model the knee as a perfect revolute joint. LOPES utilizes a revolute joint along with linear compression springs at knee for series elastic actuation of this joint. Similarly, in [24] a torsional spring based series elastic actuator is employed with a revolute joint at the knee, while in [25] a variable stiffness actuator is used to actuate a knee exoskeleton that models knee as a perfect hinge.

However, movement of human knee joint cannot be modeled as simple as a perfect hinge, since during flexion-extension of the knee tibia rolls on femur resulting in significant anterior-posterior (AP) translations. Pratt *et al.* have introduced a series elastic knee exoskeleton that *partially* supports AP translations of the knee joint thanks to its kinematic structure that utilizes two revolute joints in series [26]. This exoskeleton can provide assistance during both flexion-extension movements of the knee. A similar kinematic structure has also been used in [27] to partially allow for AP translations, while also providing assistance during the flexion movement of the knee. Note that, both of these devices can only approximate AP translations of the

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knee joint up to some degree and cannot comply with actual 3 degrees of freedom (DoF) movements of the knee taking place in the sagittal plane.

More recently, several exoskeletons that enable coupled AP translation of the knee joint along with flexion-extension movements have been introduced. In particular, Kim *et al.* have proposed a continuous passive motion machine that uses a 4-bar linkage to model specific motions of the knee joint in the sagittal plane [28]. In [29], movements of the knee in the sagittal plane are modeled using a linear actuated cam mechanism. However, given the unique nature of the knee motion for each individual, these exoskeletons necessitate off-line adjustments for every individual, such that the device joint axes closely matches human knee joint axes. Adjusting device joint axes to match the human axes is a tedious process that may take up an important portion of precious therapy duration.

More recently, knee exoskeletons that feature 3 active DoF in the sagittal plane have been introduced in [30], [31]. A planar mechanism with three revolute joints connected in series is proposed in [30], while authors have introduced a 3$\underline{R}$RP planar parallel mechanism to allow for AP translations, while assisting flexion-extensions movements of the knee [31]. In authors' previous design, the 3$\underline{R}$RP mechanism acts as a mechanical summer, superimposing the torques of three relatively small actuators to actuate flexion-extension of the knee. Thanks to this feature, the resulting exoskeleton is back-driveable; hence, allows self-alignment of the rotation axis of the exoskeleton during knee movements. Having 3 active DoF, this mechanism can also be utilized to impose desired AP translations to the knee.

Even though actuating all 3 DoF movements may be useful for certain therapies, commonly it is sufficient to only actuate flexion-extension of the knee, while being able to measure AP translations. Actuating only the rotational DoF, while keeping translational DoF under-actuated, helps keep the weight and complexity of the mechanism low. For instance, in [32], a 6 DoF knee exoskeleton with one active rotational DoF and 5 passive DoF have been proposed. Even though this device seems ideal from an ergonomic point of view, this design is relatively complex and heavy.

In this study, we present kinematics, detailed design, characterization results and initial user evaluation of a novel self-aligning active knee exoskeleton, ASSISTON-KNEE, that can provide assistance for the flexion/extension of the knee joint, while simultaneously accommodating and measuring its AP translations. In particular, ASSISTON-KNEE features 1 active rotational DoF controlled through a Bowden cable-driven series elastic actuator, and 2 passive translational DoF in the sagittal plane. ASSISTON-KNEE is based on a planar parallel kinematic chain, commonly refereed to as Schmidt Coupling [33], and possesses a singularity free workspace that can cover the whole range of motion (RoM) of knee of a healthy human. Passively adjusting its joint axis to correspond to knee axis, ASSISTON-KNEE provides an ideal match between human joint axis and the exoskeleton axis. Thanks to this feature, ASSISTON-KNEE not only guarantees ergonomy and comfort throughout the therapy, but also extends the usable RoM for the knee exoskeleton. Self-alignment feature also significantly shortens the setup time required to attach the patient to the exoskeleton. In addition to RoM measurements for the flexion/extension movements, ASSISTON-KNEE can measure AP translations, extending the type of diagnosis that can be administered using the knee exoskeletons. Furthermore, ASSISTON-KNEE possesses a light-weight and compact design with low apparent inertia, thanks to its Bowden cable based transmission that allows remote location of the actuator and reduction unit. Due to its series elastic actuation, ASSISTON-KNEE enables high-fidelity force control and active backdriveability below its control bandwidth, while it features passive elasticity for excitations above its control bandwidth, ensuring safety and robustness throughout the whole frequency spectrum.

II. KINEMATICS OF HUMAN KNEE

When considered in detail, human knee joint can be kinematically modeled as a 6 DoF joint [34]. However, since interaction of the knee joint with strong ligaments and muscles prohibit most of the DoFs significantly, models with less DoF can be utilized faithfully represents knee kinematics [35]. Even though, the flexion-extension is the dominant movement in the sagittal plane of the knee, human knee can not be modeled as a true revolute joint in this plane. In particular, during flexion-extension of the knee, tibia rolls on femur resulting in anterior-posterior (AP) translations as depicted in Figure 1. The rolling between tibia and femur results in significant amount of AP translations, with movements exceeding 19 mm in the sagittal plane, as modeled in [36], [37] and verified in [38] using x-ray measurements of human subjects. Furthermore, AP translations are coupled to the flexion-extension rotation of the knee and the exact nature of these translations strongly depends on the on physical structure of the femur and tibia and shape of the articulated surfaces. As a result, this motion is unique for every individual.

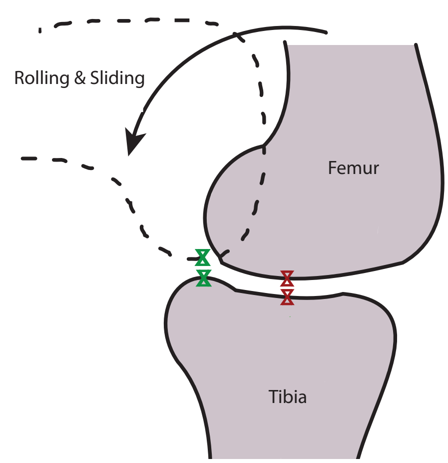

Fig. 1: Schematic representation of sagittal plane anterior-posterior translation during flexion/extension of knee joint

In addition to the flexion-extension rotation coupled with AP translations in the sagittal plane, other significant motion of human knee joint is the internal/external rotation, with a range up to $50°$ when the knee is fully flexed. However, internal/external rotation of human knee is severely constrained when it is loaded under body weight or fully extended [39].

III. Design of AssistOn-Knee

An under-actuated Schmidt-coupling is selected as the underlying mechanism for the implementation of AssistOn-Knee self-aligning knee exoskeleton, since this mechanism not only enables active control of the knee rotations, but also allows for passive translations of the exoskeleton axis throughout the knee motion. Furthermore, this mechanisms allows for the input rotation provided to be directly mapped to the knee rotation with exactly the same amount, independent of the translation of the rotation axis. Thanks to its parallel kinematic structure, the Schmidt coupling features higher rigidity and position accuracy, when compared to serial implementations of planar 3 DoF mechanisms. Moreover Schmidt coupling does not have kinematic singularities within its workspace[1] and can cover a large range of rotations, that is necessary for implementation of a knee exoskeleton with a range of motion exceeding $90°$ during flexion and extension exercises.

A. Kinematics

A Schmidt coupling is a planar mechanism possessing 3 DoF: 2 DoF translations in plane and 1 DoF rotation about the axis perpendicular to this plane [40]. The mechanism consists of seven rigid bodies: the input ring I, the intermediate ring T and the output ring E, and two links A, B connecting I to T and two more links C, D connecting T to E. During a typical implementation, two redundant connecting links (one extra at each level) are also employed for extra rigidity, symmetric force distribution and better balancing. In Figure 2, the point O is fixed at the center of I, while point Z is fixed at the center of E. Points K, L, M and Q, R, S mark revolute joints at the connection points of links A, B and C, D, respectively. The common out of the plane unit vector is denoted by $\vec{n}_3$, while basis vectors of each body are indicated in Figure 2. Symbol N depicts the Newtonian reference frame and is coincident with body I at the instant when $\theta_1 = 0$.

Let the center of output ring E with respect to the center of input ring I be expressed in the Newtonian frame as $x\,\vec{n}_1 + y\,\vec{n}_2$, while the orientation of I with respect to N be characterized by the angle θ_1. Then, the output variables can be defined as $x = \vec{r}^{OZ} \cdot \vec{n}_1$, $y = \vec{r}^{OZ} \cdot \vec{n}_2$ and $\theta_2 = atan2(\vec{e}_2.\vec{n}_2, \vec{e}_1.\vec{n}_1)$.

Forward kinematics of the mechanism can be analytically derived both at configuration and motion levels. Forward kinematics is necessary to calculate the translations of the rotation axis of output ring E. A solution to the inverse kinematics of the mechanism is not necessitated by this application, since the joint space rotations are the measured quantities.

[1]Singular configurations exist at the boundaries of ideal workspace; however, these singularities may simply be avoided by mechanically limiting the translational workspace of the mechanism to be slightly smaller than its ideal limits.

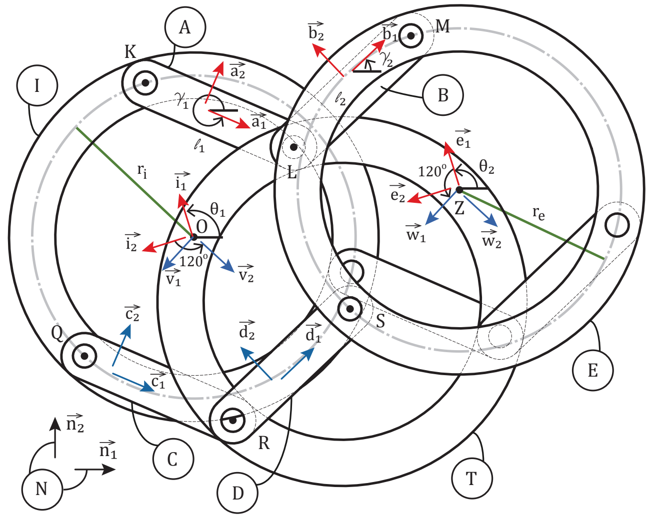

Fig. 2: Schematic diagram of Schmidt coupling

1) Configuration Level Forward Kinematics: In addition to rotation θ_1 of input link I with respect to N, the orientation of the connecting links A (and also C) and B (and also D) are measured with respect to bodies I and E and are indicated by the variables γ_1 and γ_2, respectively. For more compact representation, auxiliary reference frames V and W are introduced on the bodies I and E, respectively, by $120°$ simple rotations about $\vec{n}_3$.

Given the above definitions, the configuration level vector loop equations of the mechanism can be expressed as

$$r_i\vec{i_1} + l_1\vec{a_1} + l_2\vec{b_1} - r_e\vec{e_1} - x\vec{n_1} - y\vec{n_2} = 0 \tag{1}$$

$$r_i\vec{v_1} + l_1\vec{c_1} + l_2\vec{d_1} - r_e\vec{w_1} - x\vec{n_1} - y\vec{n_2} = 0 \tag{2}$$

Expressing all vectors in the Newtonian reference frame N, following scalar constraint equations can be derived

$$r_i\cos\theta_1 + l_1\cos\gamma_1 + l_2\cos\gamma_2 - r_e\cos\theta_2 - x = 0 \tag{3}$$

$$r_i\sin\theta_1 + l_1\sin\gamma_1 + l_2\sin\gamma_2 - r_e\sin\theta_2 - y = 0 \tag{4}$$

$$r_i\cos(\theta_1+\frac{\pi}{3}) + l_1\cos\gamma_1 + l_2\cos\gamma_2 - r_e\cos(\theta_2+\frac{2\pi}{3}) - x = 0 \tag{5}$$

When $r = r_i = r_e$, Eqns. (3) and (5) imply that θ_2 should be equal to θ_1 or have a $\pm120°$ offset with respect to θ_1. Noting that all bodies considered in the analysis are symmetric with a $120°$ circular pattern, without loss of generality, one can use the solution

$$\theta_2 = \theta_1 \tag{6}$$

indicating that the amount of input and output rotations are the same for the mechanism. Imposing equal link lengths constraint to each connecting rod, that is $l = l_1 = l_2$, the translations of the output link can be calculated as

$$x = l\cos\gamma_1 + l\cos\gamma_2 \tag{7}$$

$$y = l\sin\gamma_1 + l\sin\gamma_2 \tag{8}$$

2) Motion Level Forward Kinematics: Taking the time derivatives of the vector loop equations (Eqns. (1) – (2)) with respect to N, and projecting the resulting vector equations onto the unit vectors $\vec{n_1}$ and $\vec{n_2}$, respectively, the variables $\dot{\theta}$, $\dot{x}$ and $\dot{y}$ characterizing the angular/translational velocities of the output link O can be derived as

$$J = \begin{bmatrix} -lsin(\gamma_1) & -lsin(\gamma_2) & 0 \\ lcos(\gamma_1) & lcos(\gamma_2) & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (9)$$

with $[\dot{x}\ \ \dot{y}\ \ \dot{\theta}_2]^T = J\,[\dot{\gamma}_1\ \ \dot{\gamma}_2\ \ \dot{\theta}_1]^T$, where J represents the kinematic Jacobian J of the Schmidt Coupling.

B. Singularity Analysis and Avoidance

Analyzing the kinematic Jacobian J, singularities of the Schmidt Coupling can be located to occur when $\gamma_1 = \gamma_2$ and $\gamma_1 = -\gamma_2$. Two configurations corresponding to samples of these singularities are depicted in Figure 3. At these singularities, forces acting on the output link cannot translate the mechanism; hence, the mechanism loses its self-alignment feature. Luckily, since these singularities are located at the borders of the workspace of the mechanism, they can be avoided by mechanically limiting the workspace of the device. In particular, perfect alignment of input and output discs can be avoided by introducing overlapping pins to the center of each disk, while fully extended configuration of connecting rods can be avoided by restricting the range of motion of the output disk (see Figure 4 for an implementation of such mechanical limits in ASSISTON-KNEE).

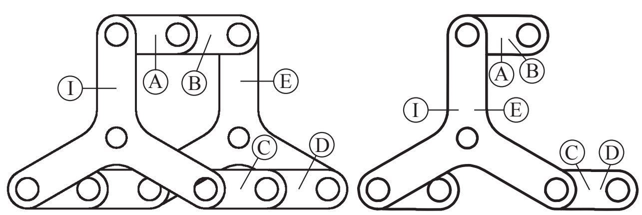

Fig. 3: Kinematic singularities at (a) $\gamma_1 = \gamma_2$ and (b) $\gamma_1 = -\gamma_2$

C. Bowden Cable-Driven Series Elastic Actuation

Figure 4 presents a solid model of ASSISTON-KNEE, which is implemented by designing a custom Schmidt Coupling to connect the thigh and shank of a patient, while the input disk of the Schmidt Coupling is actuated using a Bowden cable-driven series elastic actuator similar to that of [23]. Bowden cable enables the motor and gear reduction unit (see Figure 5) be placed away from the knee, enabling significant reduction on the weight of the knee exoskeleton. However, due to friction in Bowden cables and harmonic drive based reduction unit, the Bowden cable-driven disk is not backdriveable. To ensure high fidelity force control for assisting patients, while simultaneously reducing the output impedance of the system for safety, we have intentionally introduced compliant elements between the Bowden cable-driven disk and the input disk I. The input torque to the system is controlled by measuring the deflection between these two disks and applying Hook's

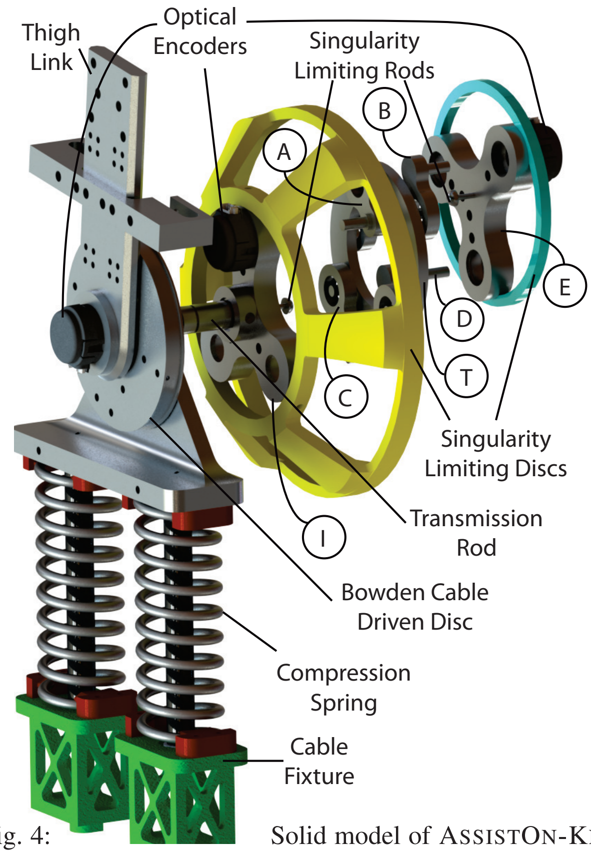

Fig. 4: Solid model of ASSISTON-KNEE

law, given the effective torsional stiffness of the elastic coupling. In particular, the design alleviates the need for high-precision force sensors/actuators/power transmission elements and allows for precise control of the force exerted by Bowden cable-driven actuator through typical position control of the deflection of the compliant coupling element. High-precision actuators/power transmission elements are not necessitated since high gain/robust position controllers can be implemented at very fast loop rates, rendering the system as a perfect motion source within the force control bandwidth of the device. Another benefit of series elastic actuation is the low output impedance of the system at the frequencies above the control bandwidth that avoids hard impacts with environment [41]. Consequently, ASSISTON-KNEE can, not only ensure backdriveability through active control at frequencies below its control bandwidth, it also features a certain level of passive elasticity for excitations above its control bandwidth, ensuring safety and robustness throughout the whole frequency spectrum.

Control bandwidth of series elastic actuators are relatively low, due to the intentional introduction of the soft coupling element [42]. Force resolution of a series elastic actuator improves as coupling is made more compliant; however, increasing compliance decreases bandwidth of the control system, trading off response time for force measurement accuracy. Even though low bandwidth of series elastic actuator limits haptic rendering performance, this does not pose an important concern for rehabilitation robots, since high fidelity rendering is not the main objective and the device

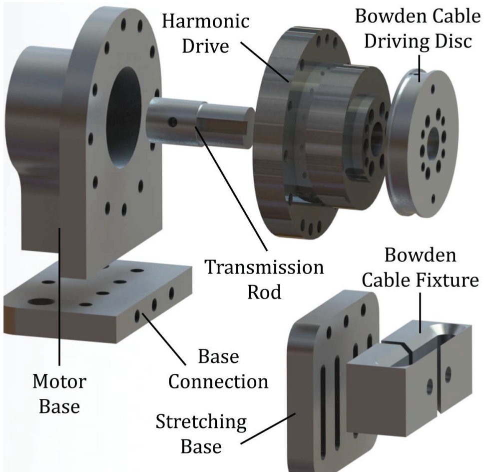

Fig. 5: Solid model of the remote actuation unit

bandwidth can still be kept higher than that of patients to provide adequate levels of haptic assistance.

Figure 6 presents a functional prototype of ASSISTON-KNEE. A commercial knee brace is utilized to attach the exoskeleton to thigh and shank of the patient, while thigh and shank links are connected to each other through a custom built Schmidt Coupling on one side, and an unactuated RRR serial mechanism on the other. The RRR serial mechanism helps with the structural integrity of the exoskeleton, while not restricting its movements in sagittal plane. Since ASSISTON-KNEE is self-aligning, the exoskeleton can be worn in less than a minute.

The Schmidt Coupling is actuated by a series elastic actuator driven by Bowden cables. Bowden cable drive enables the actuator and harmonic drive to be remotely located, resulting in a light weight design with low apparent inertia. The part of the exoskeleton that is connected to human limbs weighs less than 1.4 kg. The remotely located actuation unit for the Bowden cables utilizes a 200W graphite brushed DC motor instrumented with an optical incremental encoder. A harmonic drive with a reduction ratio of 1:50 is used together with a Bowden cable disc ratio of 4:7 to deliver up to 35.5 Nm continuous torque to actuate flexion/extension rotations of the knee joint. The shields of Bowden cables are attached to a fixture that allows for easy tensioning of the cables as presented in Figure 5 and 7. However, friction introduced to the system increases as the cables are bent with smaller radius.

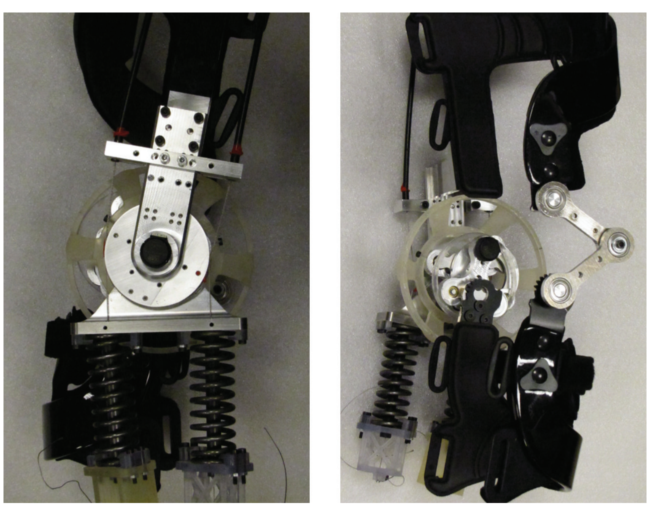
Fig. 6: Prototype of Bowden cable-driven series elastic ASSISTON-KNEE


Fig. 7: ASSISTON-KNEE and its remote actuation unit

Incremental encoders are attached to the Schmidt coupling to measure relative rotations of the input disc I and the connection rods C and D. Thus, forward kinematics can easily be calculated.

IV. CHARACTERIZATION OF THE KNEE EXOSKELETON

Table I presents the characterization results for ASSISTON-KNEE. Instantaneous peak and continuous end-effector torques are determined as 780 Nm and 35.5 Nm, respectively. The end-effector resolutions are calculated to be less than 0.05 mm for translations of the knee and $0.2°$ for rotations. Two linear compression springs with a spring rate of 10 N/mm are used to estimate the joint torque with resolution of 0.0025 Nm, while resulting in a device stiffness of 26 Nm/rad. The exoskeleton possesses a translational workspace that spans an area between two (singularity limiting) circles of radiuses 1 mm and 24 mm, while it is capable of performing up to $180°$ rotations about the perpendicular axis. Mechanical stops are utilized to limit the rotational range to match the requirements of the rehabilitation task. Specifications of ASSISTON-KNEEare selected to closely match the specifications of a commercial knee exoskeleton with clinical use [43].

TABLE I: Characterization of ASSISTON-KNEE

Criteria	X	Y	Z
Peak Torque	N/A	N/A	780 [Nm]
Cont. Torque	N/A	N/A	35.5 [Nm]
Max. Speed	N/A	N/A	65 [rpm]
Min. Res. Torque	N/A	N/A	0.0025 [Nm]
Device Stiffness	N/A	N/A	26 [Nm/rad]
Resolution	0.047 [mm]	0.047 [mm]	0.18 [°]
Workspace	-24 – 24 [mm]	-24 – 24 [mm]	-10° – 170°

V. User Evaluations

To test feasibility and useability of AssistOn-Knee to assist knee movements, firstly we have tested flexion/extension movements of healthy volunteers under closed-loop position of the robot. In particular, rotational flexion/extension movement is imposed to the subject, while AP translations in the sagittal plane are measured. Utilizing a position controller, a 2.5 Hz sinusoidal reference trajectory with 60° magnitude is imposed to the input disc of the Schmidt Coupling to carry out the knee flexion/extension, while volunteers are attached to AssistOn-Knee. Figure 8 presents AP translations of the knee measured during such a sample trial. Here, encirclements refer to flexion/extension angle of the knee. One can observe from Figure 8 that, as expected, knee follows a distinct closed loop trajectory during flexion and extension. AssistOn-Knee is capable of measuring AP translations, which may be useful for diagnostic purposes.

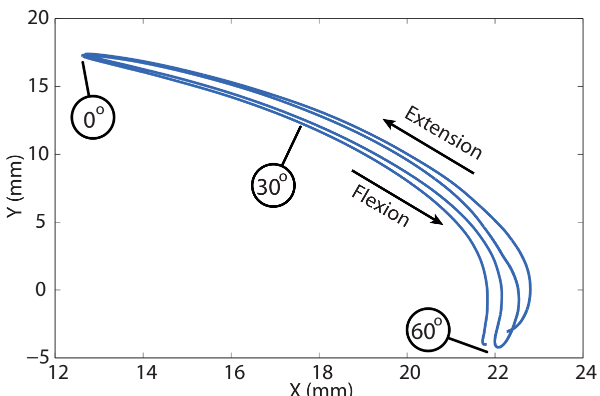

Fig. 8: Knee joint center displacement

Secondly, torque tracking performance of AssistOn-Knee is tested under explicit force control. Figure 9 presents sample results from torque tracking experiments during which the device is worn by a volunteer and a sinusoidal torque reference is to be followed. With an RMS error of 74.3 mNm in Figure 9, the torque tracking performance of AssistOn-Kneecan be observed to be quite satisfactory for rehabilitation exercises. Small amplitude high frequency torque ripples due to stick-slip friction and quantization noise can be observed in the close-up view of torque trajectories, however, torque ripples are mechanically low pass filtered by the spring elements before being applied to the user.

Finally, to demonstrate the effectiveness of the assistance provided by AssistOn-Knee, user effort for flexion and extension of knee is compared during a standing up task with and without assistance. In particular, EMG signals are recorded from medial hamstring and quadriceps femoris for the flexion and extension of the knee, respectively. In Figure 10, normalized EMG signals with and without assistance are plotted for multiple trials. The solid lines in the figure represent average values, while the shaded areas around these solid lines cover the recorded EMG trajectories from all trials. The EMG trajectories suggest that AssistOn-Knee is quite effective in decreasing the effort required for extension during a standing up task.

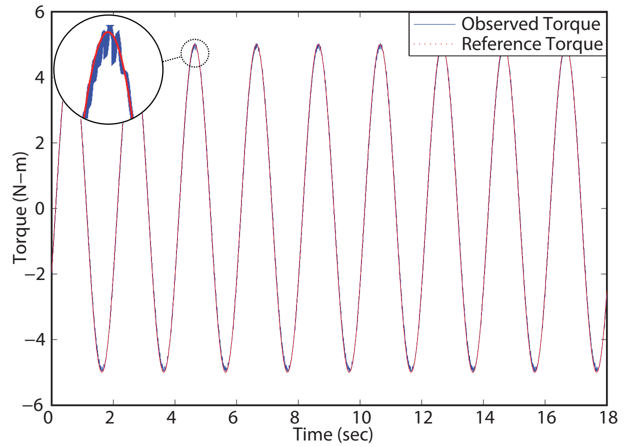

Fig. 9: Torque tracking performance of AssistOn-Knee under a sinusoidal torque reference

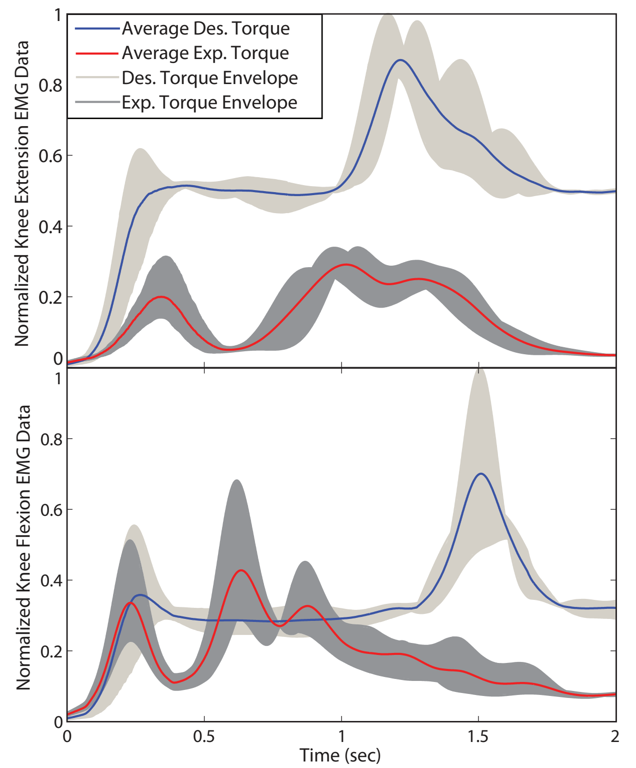

Fig. 10: Normalized EMG signal levels for knee flexion and extension muscles during a standing up task with and without assistance

VI. Conclusion and Future Works

We have introduced kinematics of AssistOn-Knee, presented its design details, Bowden cable-driven series elastic actuation and characterization results. We have also conducted feasibility studies on healthy volunteers and showed usability of AssistOn-Knee during flexion/extension movements, while allowing for natural AP translations of individuals.

Our future work includes larger scale human subject experiments and tracking of human gait with/without the device to verify that the devices does not interfere with natural walking gait of its users. Furthermore, case studies with stroke patients are to be scheduled with the device.

REFERENCES

[1] G. B. Prange, M. J. Jannink, C. G. Groothuis-Oudshoorn, H. J. Hermens, and M. J. Ijzerman, "Systematic review of the effect of robot-aided therapy on recovery of the hemiparetic arm after stroke," *Journal of rehabilitation research and development*, vol. 43, no. 2, pp. 171–184, 2006.

[2] G. Kwakkel, B. J. Kollen, and H. I. Krebs, "Effects of robot-assisted therapy on upper limb recovery after stroke: A systematic review," *Neurorehabilitation and Neural Repair*, vol. 22, no. 2, pp. 111–121, 2008.

[3] J. Mehrholz, T. Platz, J. Kugler, and M. Pohl, "Electromechanical and robot-assisted arm training for improving arm function and activities of daily living after stroke," *Stroke*, vol. 40, pp. e292–e293, 2009.

[4] K. Nykanen, "The effectiveness of robot-aided upper limb therapy in stroke rehabilitation: A systematic review of randomized controlled studies," Master's thesis, University of Jyvaskyla, Institute of Health Sciences, Physiotherapy, 2010.

[5] N. Hogan, H. Krebs, J. Charnnarong, P. Srikrishna, and A. Sharon, "Mit-manus: a workstation for manual therapy and training. i," in *IEEE International Workshop on Robot and Human Communication*, Sep 1992, pp. 161–165.

[6] A. Frisoli, F. Rocchi, S. Marcheschi, A. Dettori, F. Salsedo, and M. Bergamasco, "A new force-feedback arm exoskeleton for haptic interaction in virtual environments," in *Eurohaptics Conference, Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems. World Haptics 2005. First Joint*, March 2005, pp. 195–201.

[7] R. Ekkelenkamp, J. Veneman, and H. van der Kooij, "Lopes: a lower extremity powered exoskeleton," in *IEEE International Conference on Robotics and Automation*, April 2007, pp. 3132–3133.

[8] B. Vanderborght, N. Tsagarakis, C. Semini, R. Van Ham, and D. Caldwell, "Maccepa 2.0: Adjustable compliant actuator with stiffening characteristic for energy efficient hopping," in *IEEE International Conference on Robotics and Automation*, May 2009, pp. 544–549.

[9] F. Wang, D. Barkana, and N. Sarkar, "Impact of visual error augmentation when integrated with assist-as-needed training method in robot-assisted rehabilitation," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 18, no. 5, pp. 571–579, Oct 2010.

[10] A. C. Satici, A. Erdogan, and V. Patoglu, "A multi-lateral rehabilitation system," *Turkish Journal of Electrical Engineering and Computer Sciences*, vol. 19, no. 5, pp. 715–723, 2011.

[11] A. Erdogan and V. Patoglu, "Slacking prevention during assistive contour following tasks with guaranteed coupled stability," in *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), 2012*, Oct., pp. 1587–1594.

[12] A. Schiele and F. van der Helm, "Kinematic design to improve ergonomics in human machine interaction," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 14, no. 4, pp. 456–469, Dec. 2006.

[13] A. Stienen, E. Hekman, F. van der Helm, and H. van der Kooij, "Self-aligning exoskeleton axes through decoupling of joint rotations and translations," *IEEE Transactions on Robotics*, vol. 25, no. 3, pp. 628–633, June 2009.

[14] M. Cenciarini and A. M. Dollar, "Biomechanical considerations in the design of lower limb exoskeletons," in *IEEE International Conference on Rehabilitation Robotics*, 2011, pp. 1–6.

[15] P. S. Lum, S. Mulroy, R. L. Amdur, P. Requejo, B. I. Prilutsky, and A. W. Dromerick, "Gains in upper extremity function after stroke via recovery or compensation: Potential differential effects on amount of real-world limb use," *Topics in Stroke Rehabilitation*, vol. 16, no. 4, pp. 237–253, 2009.

[16] D. Caldwell, C. Favede, and N. Tsagarakis, "Dextrous exploration of a virtual world for improved prototyping," in *IEEE International Conference on Robotics and Automation*, 1998, pp. 298–303.

[17] C. Carignan, M. Liszka, and S. Roderick, "Design of an arm exoskeleton with scapula motion for shoulder rehabilitation," in *12th International Conference on Advanced Robotics*, 2005, pp. 524–531.

[18] T. Nef, M. Guidali, and R. Riener, "Armin iii - arm therapy exoskeleton with an ergonomic shoulder actuation," *Applied Bionics and Biomechanics*, vol. 2, no. 6, pp. 127–142, 2009.

[19] M. Yalcin and V. Patoglu, "Kinematics and design of assiston-se: A self-adjusting shoulder-elbow exoskeleton," in *IEEE International Conference on Biomedical Robotics and Biomechatronics*, 2012, pp. 1579–1585.

[20] "Jaipur knee," http://remotiondesigns.org/jaipurknee.html.

[21] V. Cai, P. Bidaud, V. Hayward, and F. Gosselin, "Design of self-adjusting orthoses for rehabilitation," in *IASTED International Conference on Robotics and Applications*, 2009, pp. 215–223.

[22] R. Riener, L. Lünenburger, and G. Colombo, "Human-Centered Robotics Applied to Gait Training and Assessment," *Veterans Admin. Journal of Rehabilitation Research and Development*, pp. 679–694, 2006.

[23] J. F. Veneman, "Design and evaluation of the gait rehabilitation robot lopes," Ph.D. dissertation, Enschede, December 2007.

[24] F. Sergi, D. Accoto, G. Carpino, N. L. Tagliamonte, and E. Guglielmelli, "Design and characterization of a compact rotary series elastic actuator for knee assistance during overground walking," in *IEEE RAS & EMBS International Conference on Biomedical Robotics and Biomechatronics*, 2012, pp. 1931–1936.

[25] N. C. Karavas, N. G. Tsagarakis, and D. G. Caldwell, "Design, modeling and control of a series elastic actuator for an assistive knee exoskeleton," in *IEEE RAS & EMBS International Conference on Biomedical Robotics and Biomechatronics*, 2012, pp. 1813–1819.

[26] J. E. Pratt, B. T. Krupp, C. J. Morse, and S. H. Collins, "The roboknee: an exoskeleton for enhancing strength and endurance during walking," in *IEEE International Conference on Robotics and Automation*, 2004, pp. 2430–2435.

[27] J. S. Sulzer, R. A. Roiz, M. A. Peshkin, and J. L. Patton, "A highly backdrivable, lightweight knee actuator for investigating gait in stroke," *IEEE Transactions on Robotics*, vol. 25, no. 3, pp. 539–548, 2009.

[28] K. J. Kim, M. S. Kang, Y. S. Choi, J. Han, and C. Han, "Conceptualization of an exoskeleton continuous passive motion (cpm) device using a link structure," in *IEEE International Conference on Rehabilitation Robotics*, 2011, pp. 1–6.

[29] D. Wang, J. Guo, K. M. Lee, C. Yang, and H. Yu, "An adaptive knee joint exoskeleton based on biological geometries," in *IEEE International Conference on Robotics and Automation*, 2011, pp. 1386–1391.

[30] L. E. Amigo, A. Casals, and J. Amat, "Design of a 3-dof joint system with dynamic servo-adaptation in orthotic applications," in *IEEE International Conference on Robotics and Automation*, 2011, pp. 3700–3705.

[31] M. A. Ergin and V. Patoglu, "A self-adjusting knee exoskeleton for robot-assisted treatment of knee injuries," in *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, Sept. 2011, pp. 4917–4922.

[32] V. A. D. Cai, P. Bidaud, V. Hayward, F. Gosselin, and E. Desailly, "Self-adjusting, isostatic exoskeleton for the human knee joint," in *Annual International Conference of the IEEE Engineering in Medicine and Biology Society*, 2011, pp. 612–618.

[33] (2013, July) Schmidt-kupplung: Specialist for compact precision couplings. [Online]. Available: http://www.schmidt-kupplung.com/sk/1575_schmidt-kupplung.com.html.en

[34] J. Apkarian, S. Naumann, and B. Cairns, "A three-dimensional kinematic and dynamic model of the lower limb," *Journal of Biomechanics*, vol. 22, no. 2, pp. 143–155, 1989.

[35] L. Blankevoort and R. Huiskes, "Validation of a three-dimensional model of the knee," *Journal of Biomechanics*, vol. 29, no. 7, pp. 955–961, 1996.

[36] J. Bellmans, J. Bellemans, and M. D. Ries, *Total Knee Arthroplasty: A Guide to Get Better Performance*. Springer Berlin Heidelberg, 2005, pp. 130–134.

[37] K.-M. Lee and J. Guo, "Kinematic and dynamic analysis of an anatomically based knee joint," *Journal of Biomechanics*, vol. 43, no. 7, pp. 1231–1236, 2010.

[38] A. Williams and M. Logan, "Understanding tibio-femoral motion," *The Knee*, vol. 11, no. 2, pp. 81–88, 2004.

[39] N. Hamilton, W. Weimar, and K. Luttgens, *Kinesiology: Scientific Basis of Human Motion*. New York, NY: McGraw-Hill, 2012.

[40] R. Schmidt, "Coupling," Patent US 3 791 170, Feb 12, 1974.

[41] J. W. Sensinger and R. F. f. Weir, "Improvements to series elastic actuators," in *IEEE/ASME International Conference on Mechatronic and Embedded Systems and Applications*, 2006.

[42] G. A. Pratt and M. M. Williamson, "Series elastic actuators," in *IEEE International Conference on Intelligent Robots and Systems*, 1995.

[43] R. W. Horst, "A bio-robotic leg orthosis for rehabilitation and mobility enhancement," in *Annual International Conference of the IEEE Engineering in Medicine and Biology Society*, 2009, pp. 5030–5033.