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System for Compensating for Leg Length Discrepancy Based on the Estimation of the Centre of Mass of a Human Body

Zoran Vrhovski[1], Goran Benkek[1], Alan Mutka[1,2], Karlo Obrovac[2] and Stjepan Bogdan[3]

Abstract— **This paper presents a system for compensating for leg length discrepancy (LLD) based on the estimation of the centre of mass of a human body. The system consists of two 3-RPS parallel manipulators with a moving force plate, control and measuring electronics and a graphical user interface (GUI). Force plates are equipped with force sensors that estimate the centre of mass (CoM) of a human body. Patients with LLD have a displaced CoM. By increasing the height of the force plate that measures a greater load, the CoM of a human body returns into the correct position. The height of the force plate is regulated by means of the 3-RPS parallel manipulator. LLD is compensated for by the difference in heights of the force plates. This paper presents the preliminary experimental results of the system for compensating for LLD.**

I. Introduction

Leg Length Discrepancy (LLD) is an orthopaedic condition that involves a difference in length between the lower extremities. A significant amount of LLD is the one greater than 20 mm [1]. Patients with LLD have a displaced centre of mass (CoM), which causes bad posture, low back pain and inefficient and energy-consuming walking and running. The quality of life of patients with LLD may be improved by means of clinical and non-clinical treatments whose purpose is to compensate for LLD. An overview of treatments is presented in article [1].

The accuracy and reliability of LLD estimation is essential for determining the required treatment of compensating for LLD. The methods for LLD estimation are divided into Clinical Methods and Imaging Methods. An overview and comparison of estimation methods are presented in [2].

Authors in [3] showed that it is possible to use pedobarograph for measuring the difference in the load of the left leg by simulating shortening / lengthening of the right leg. The simulation of lengthening the patient's right leg by 3.5 cm resulted in the load of the left leg amounting to 64 % of the patient's total mass [3]. In-shoe paedobarograph system was used for measuring the load of the left and right leg of patients with LLD in article [4]. The authors showed that there was a measurable difference between the load of the left and right leg in patients with LLD.

[1]Zoran Vrhovski, Goran Benkek and Alan Mutka are with Bjelovar University of Applied Sciences, Trg E. Kvaternik 4, 43000 Bjelovar, Croatia, zvrhovski@vub.hr, gbenkek@vub.hr, amutka@vub.hr

[2] Alan Mutka and Karlo Obrovac are with Cognitus Ltd., Remetinec 42, 10000 Zagreb, Croatia, alan.mutka@cognitus.hr, karlo.obrovac@cognitus.hr

[3] Stjepan Bogdan is with Faculty of Electrical Engineering and Computing, University of Zagreb, Unska 3, 10000 Zagreb, Croatia stjepan.bogdan@fer.hr

The existing methods of LLD estimation are not reliable. Furthermore, they subject patients to radiation and do not account for the displacement of CoM of the human body. In articles [3] and [4] authors showed that there was a displacement of CoM in patients with LLD, but they did not provide a solution for estimating the amount of LLD based on the CoM displacement.

This paper describes the construction of the system for compensating for LLD based on the estimation of CoM of a human body. This system consists of two 3-RPS (Revolute-Prismatic-Spherical) parallel manipulators with moving force plates, control and measuring electronics and graphical user interface (GUI) for controlling parallel manipulators and presenting the measured forces from force plates. LLD compensation is performed in the following manner. A patient with LLD stands on the left and right force plate. A force plate has four force sensors. Sensors measure the centre of pressure (CoP) of the foot and the total force that the foot exerts on the force plate. The patient's shorter leg creates a greater load for the force plate. LLD compensation is performed by means of GUI by increasing the height of the force plate below the shorter leg by means of a 3-RPS manipulator. The height of the force plate is increased up to the moment when the measured forces of the left and right force plate become equal. The difference in height of the force plates represent the amount of LLD and may be used for making the insole for compensating for LLD. The height of the force plate may be calculated by using the direct and inverse kinematics described in articles [5] and [6]. The construction of the mechanical part of the system was preceded by the 3D design of the system that is described in article [6] and presented on YouTube [7].

The paper is organised as follows. Section II describes the system for compensating for LLD based on the estimation of CoM of a human body. Section III describes 3-RPS parallel manipulators with moving force plates as well as the control and measuring electronics. Section IV presents software solutions used in this paper, while Section V involves experimental results. A short conclusion and future prospects of the work are to be found in Section VI.

II. System Design

The design of the system for compensating for LLD is based on the following demands originating from an orthopaedic clinic:

- the system should allow for measuring the position of CoM of a human body by means of two force plates (below both the left and the right leg),

- the system should be able to change the height and inclination of the left and right force plate,
- the system should be able to determine the height of the orthopaedic insole used for compensating for LLD based on the estimation of CoM of a human body,
- upon upgrading it, the system should be able to be used for the purpose of foot rehabilitation and walking simulation,
- the system should be simple to use,
- the system should allow for obtaining reliable data.

The system for compensating for LLD is shown in Figure 1. This system consists of:

- mechanical part that includes two 3-RPS parallel manipulators with a moving force plate,
- control and measuring electronics,
- body tracking system,
- graphical user interface (GUI).

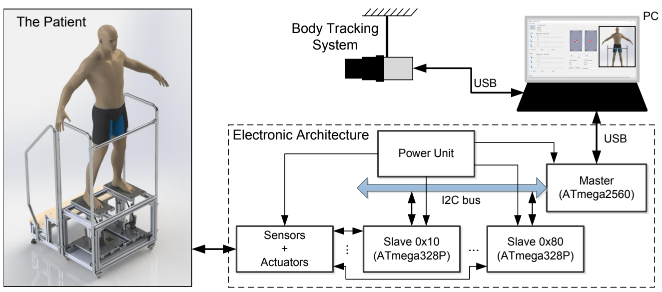


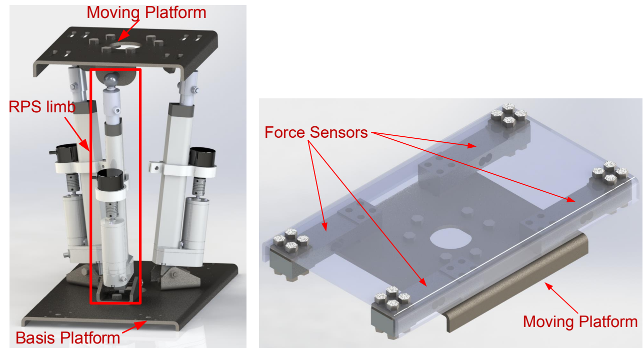
Fig. 1: System for compensating for LLD

3-RPS parallel manipulators have three degrees of freedom (DOF): translation along the z axis, rotation around the x axis (roll) and rotation around the y axis (pitch) [8]. In the construction of the system for compensating for LLD, 3-RPS parallel manipulators are used due to their advantages: the ability to manipulate high loads, high rigidity, low weight, the fact that they take up little space and are very accurate in positioning. 3-RPS parallel manipulators have a moving platform and a basis platform that are connected with three identical RPS actuators (see Figure 2a). RPS actuators of a parallel manipulator have rotate, prismatic and spherical joints. Prismatic joints are electrical linear actuators that may change their length. A change in length of the linear actuators results in a change of height and inclination of the moving platform [9]- [11]. A force plate is mounted on the moving platform of the 3-RPS parallel manipulator (see Figure 2b). The force plate has four force sensors in its corners. Force sensors are used for measuring the centre of pressure (CoP) of the patient's left and right leg.

The control and measuring electronics consists of a single Master device and eight Slave devices. This part of the system controls the height and inclination of the moving platform of 3-RPS parallel manipulators and measures force by means of force sensors located on the force plate.

Body tracking system involves the application of the Microsoft Kinect device. The Kinect device is used for the purpose of detecting a patient standing at rest on force plates.

GUI transfers the reference positions of linear actuators to the control electronics and receives the current values of the positions of linear actuators via the measuring electronics as well as the measured force from the force plates.



(a) 3-RPS

(b) Force plate

Fig. 2: Mechanical part of the system for compensating for LLD: a) 3-RPS parallel manipulator. b) Force plate

The system shown in Figure 1 is used for estimating the CoM of a human body for the purpose of compensating for LLD. The compensation is carried out by lifting one of the moving force plates of the 3-RPS parallel manipulator. The patient stands with both legs on the force plates (see Figure 1). Patients with LLD have a displaced CoM. Due to this, the total measured force on one force plate will be greater than the measured force on the other force plate. GUI is used for increasing the height of the moving force plate that measures a greater load. The height of the force plate with a greater load is increased up to the moment when CoM reaches the correct position. This results in LLD compensation. This procedure represents balancing of a human body and it is performed manually. For the purpose of controlling the height of a 3-RPS parallel manipulator it is necessary to solve the inverse and direct kinematics of a 3-RPS parallel manipulator as described in articles [5] and [6].

III. Hardware Design

A. Mechanical design

The mechanical part of the system for compensating for LLD consists of two equal 3-RPS parallel manipulators with moving force plates. Parts of the left and right 3-RPS parallel manipulator with moving force plates are shown in Figure 3. The basis platform is made of sheet metal whose thickness amounts to 5 mm. Three carriers for revolute joints are mounted on the basis platform. The carriers are made of bent sheet metal whose thickness amounts to 5 mm. Revolute joints are geometrically positioned in the vertices of an isosceles triangle with the diameter of circumscribed circle amounting to 120 mm [5].

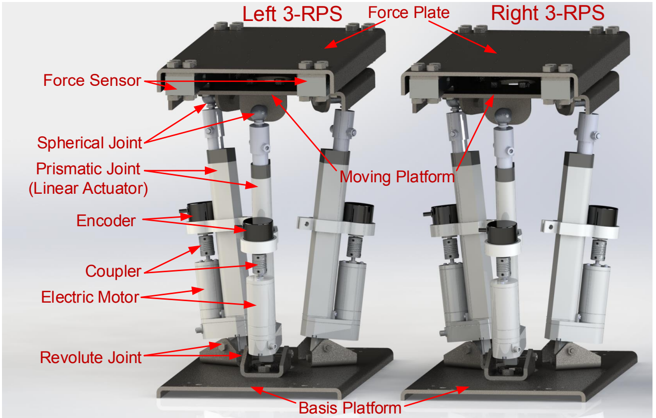


Fig. 3: Left and right 3-RPS parallel manipulator with moving force plates

Linear actuators (prismatic joints) are connected to revolute joints. A linear actuator is driven by a DC electric motor with the nominal voltage amounting to 12 V. The maximal thrust force of the linear actuator amounts to 1.500 N, while the maximal speed of the linear actuator amounts to 5.7 mm s^{-1}. The minimal length of linear actuator amounts to 260 mm, while its maximal length amounts to 410 mm. An incremental encoder is attached to the body of the linear actuator. The incremental encoder shaft is connected to the DC motor rotor shaft by means of a coupling. Incremental encoder is used for measuring the position of a linear actuator.

A spherical joint is mounted on the upper side of the linear actuator. Spherical joints connect linear actuators with the moving platform. Linear actuators may change the height and inclination of the moving platform. Spherical joints are geometrically positioned in the vertices of an isosceles triangle with the diameter of circumscribed circle amounting to 200 mm [5]. Moving platform is made of sheet metal whose thickness amounts to 5 mm. A force plate is mounted on the moving platform (see Figure 2b). The force plate contains four force sensors that are geometrically positioned in the vertices of a rectangle with dimensions amounting to 168 $\times$ 361 mm. Force sensors are used for determining the CoP of the patient's leg.

B. Electronic design

The electronic part of the system for compensating for LLD (control and measuring electronics) consists of a single Master device and eight Slave devices that are mutually connected by an I^2C bus (see Figure 1). Slave devices have a unique address for the purpose of avoiding collision on the I^2C bus. The Master device is an ATmega2560 microcontroller. It is connected to a PC via USB communication.

Electronic architecture of Slave devices is shown in Figure 4. It includes an ATmega328P microcontroller, a HX711 analogue-digital (A/D) converter, a force sensor, a linear actuator, an L298 motor driver, an incremental encoder, a connector and auxiliary electronic components.

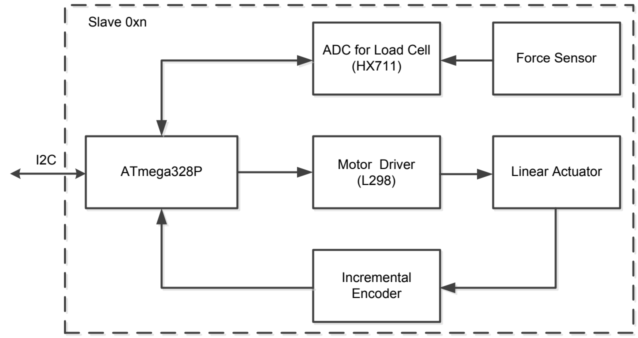


Fig. 4: Electronic architecture of Slave devices

The force plate contains four force sensors (see Figure 2b) that generate an electric signal with the amplitude proportional to the force acting upon the sensors. Force sensor is connected to the electronic module HX711, which is a high-precision 24-Bit A/D converter with programmable amplification amounting to 32, 64 and 128. The output rate of the A/D converter amounts to 10 samples per second. This electronic module amplifies the electric signal from the force sensor and converts it into a 24-bit digital word. HX711 is connected to the ATmega328P microcontroller that receives digital word in the form of a serial sequence of impulses. Before being used, force sensors are calibrated by means of a weight whose mass amounts to 200 g.

The height and inclination of the moving platform of the 3-RPS manipulator are changed as the position of linear actuators is changed. An L298 motor driver and an incremental encoder are used for controlling the position of linear actuators. L298 is a motor driver with two H-bridges. The L298 motor driver is connected to the PWM (Pulse Width Modulation) output of the ATmega328P microcontroller in order to achieve variable speed of the linear actuator. Incremental encoder is used for measuring the position of the linear actuator. The resolution of the incremental encoder amounts to 360 impulses per rotation. As the position of the linear actuator changes by 1 mm, incremental encoder produces 5523 impulses. Incremental encoder has two channels: channel A and channel B. Channels A and B are connected to the pins of external interrupts of the ATmega328P microcontroller and allow for detecting the movement direction of the linear actuator.

Master device sends the reference position of linear actuators to Slave devices. Slave devices send current positions of linear actuators and measured forces from force sensors to the Master device.

IV. Software Design

A. Microcontroler

Microcontroller programs are written in the Atmel Studio 7.0 integrated development environment (IDE). The C programming language was used. The microcontroller program (ATmega2560) on the Master device deals with the communication with the PC and Slave devices. As the system is initialised, the Master device sends the order to Slave devices to set the 3-RPS parallel manipulators in Hard Home Position. After that, the Master device sends the order to Slave devices to set the linear actuators of the 3-RPS parallel manipulators in the initial position amounting to 20 mm. The main microcontroller program of the Master device sends the order to Slave devices every 50 ms to deliver measured forces from the force sensor and the current position of linear actuators. It sends these data to the PC in the form of a data framework. Simultaneously the microcontroller waits for the data framework from the PC about the position of linear actuators and forwards it to Slave devices.

The microcontroller program (ATmega328P) on Slave devices handles tasks according to the order given by the Master device. Slave devices send measured forces from force sensors and the current position of linear actuators to the Master device. Slave devices receive reference positions of linear actuators from the Master device and set them in the reference positions.

B. Graphical User Interface

For the purpose of presenting the measured data of the system for compensating for LLD and controlling the reference positions of linear actuators, a graphical user interface (GUI) was made (see Figure 5). GUI was made in Visual Studio 2017 IDE. The C# program language was used.

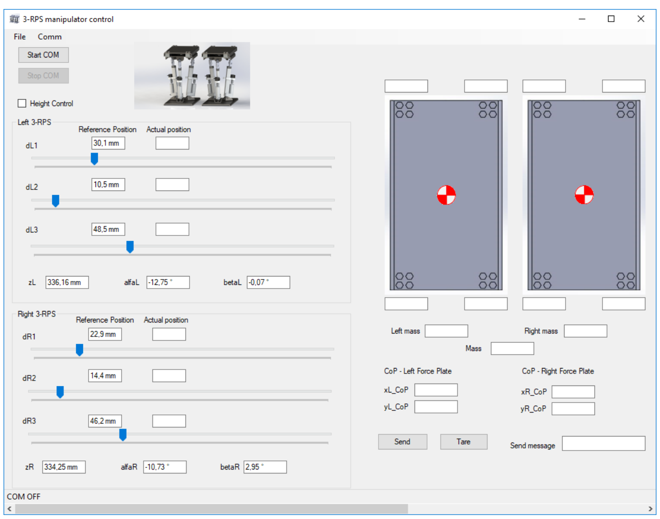


Fig. 5: Graphical User Interface of the system for compensating for LLD

GUI allows for sending reference positions of linear actuators to the Master device. Reference positions of linear actuators reach values from 0 to 150 mm with the precision of 0.1 mm. In GUI background the inverse kinematics problem (IKP) and the forward kinematics problem (FKP) of the 3-RPS parallel manipulator are implemented, as described in articles [5] and [6]. FKP solutions are shown on GUI (platform height z [mm], rotation around the x axis α [°] and rotation around the y axis β [°]).

GUI shows measured forces from all force sensors, the sum of forces from the left and right force plate and the total force from all force sensors. GUI calculates and draws CoP for each force plate individually. Measured forces from all force sensors, reference and current positions of linear actuators are entered in a textual file for the purpose of measurement analysis upon measuring.

V. Experimental Results

For the purpose of testing LLD compensation by means of estimating the CoM of a human body, a prototype of the system for compensating for LLD was made. The prototype of the system for compensating for LLD is shown in Figure 6. Figure 7 shows the front side of the system for compensating for LLD where two 3-RPS parallel manipulators with moving force plates are visible. The position of CoM determines whether the human body is in balance. CoM of the human body cannot be determined directly, but by means of estimation using CoP. CoP may be calculated directly by measuring forces on force plates.

Fig. 6: Prototype of the system for compensating for LLD

The coordinate systems in the horizontal (transversal) plane of the left and right force plate of the system for compensating for LLD are shown in Figure 8. CoP of the left and right leg is expressed in a local coordinate system of the left and right force plate. The distance between the force sensors along the x axis amounts to a = 168 mm. The distance between force sensors along the y axis amounts to b = 361 mm. The distance between the origins of the left and right coordinate system of force plates amounts to l = 265 mm.

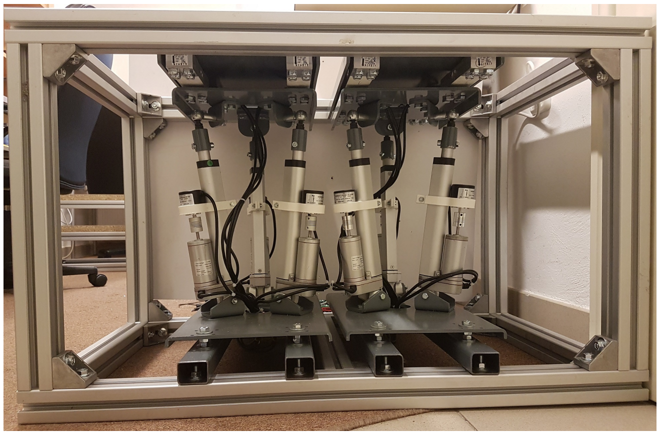


Fig. 7: Prototype of the system for compensating for LLD: two 3-RPS parallel manipulators with moving force plates

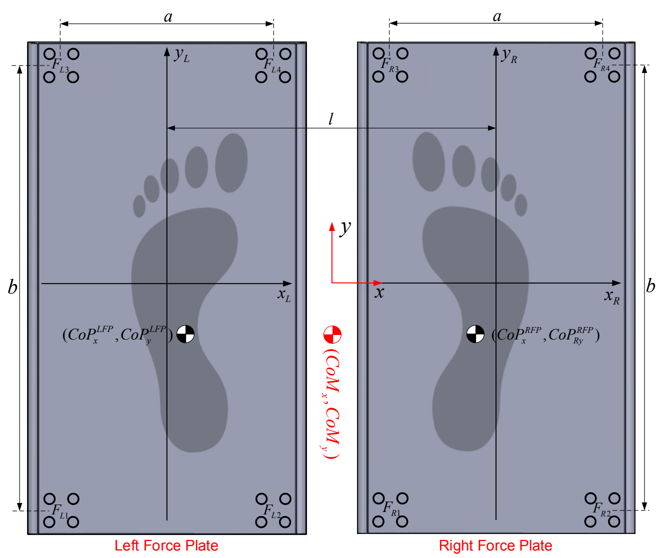


Fig. 8: Coordinate systems and dimensions of the left and right force plate

Measured forces of the left force plate are F_{L1}, F_{L2}, F_{L3} and F_{L4}. Measured forces of the right force plate are F_{R1}, F_{R2}, F_{R3} and F_{R4}.

In the local coordinate system of the left force plate CoP is defined by means of equations (1) [12], [13].

$$\begin{aligned} CoP_x^{LFP} &= \frac{\frac{a}{2}(F_{L2}+F_{L4})-\frac{a}{2}(F_{L1}+F_{L3})}{F_L} \\ CoP_y^{LFP} &= \frac{\frac{b}{2}(F_{L3}+F_{L4})-\frac{b}{2}(F_{L1}+F_{L2})}{F_L} \end{aligned} \tag{1}$$

where F_L is the sum of measured forces of the left force plate. In the local coordinate system of the right force plate CoP is defined by means of equations (2).

$$\begin{aligned} CoP_x^{RFP} &= \frac{\frac{a}{2}(F_{R2}+F_{R4})-\frac{a}{2}(F_{R1}+F_{R3})}{F_R} \\ CoP_y^{RFP} &= \frac{\frac{b}{2}(F_{R3}+F_{R4})-\frac{b}{2}(F_{R1}+F_{R2})}{F_R} \end{aligned} \tag{2}$$

where F_R is the sum of measured forces of the right force plate. The coordinates of CoP of the left and right force plate in the global xy coordinate system may be represented by the equation (3).

$$\begin{aligned} (CoP_{xL}, CoP_{yL}) &= \left(CoP_x^{LFP} - \tfrac{l}{2}, CoP_y^{LFP}\right) \\ (CoP_{xR}, CoP_{yR}) &= \left(CoP_x^{RFP} + \tfrac{l}{2}, CoP_y^{RFP}\right) \end{aligned} \tag{3}$$

By substituting equations (1) and (2) in equation (3), the expression for the CoP of a human body in the xy global coordinate system is obtained:

$$\begin{aligned} CoP_x &= \frac{CoP_{xL}F_L + CoP_{xR}F_R}{F_L+F_R} \\ CoP_y &= \frac{CoP_{yL}F_L + CoP_{yR}F_R}{F_L+F_R} \end{aligned} \tag{4}$$

In ideally restful posture, CoM projection in the horizontal plane is located in the same point as CoP. Due to postural sway, CoM projection will deviate from CoP. If a patient standing on a force plate keep their posture at rest, the amplitude of postural sway will be very low [14]. Body tracking system (Microsoft Kinect) is used for detecting the moment of standing at rest. At the moment of standing at rest CoM coordinates in the horizontal plane may be estimated by using the equation (5).

$$(CoM_x, CoM_y) \approx (CoP_x, CoP_y) \tag{5}$$

While estimating the patient's CoM, the patient must set their feet and stand on marked positions. Incorrect standing on force plates may lead to unreliable results. In the global coordinate system xy human body will be in balance when the following is valid: $CoM_x = 0$. Balance in patients with LLD is achieved by increasing the height of the force plate that measures a greater force. The difference in height of force plates δz is the amount of LLD compensation. This information may be used while designing orthopaedic insoles for LLD patients.

Simulation results of the system for compensating for LLD are presented in article [5]. Experimental results of the system for compensating for LLD are presented below on the example of a healthy adult whose left and right leg are of equal length. The right force plate is of initial height amounting to z_{R0} = 330.5 mm, while the left force plate is of initial height amounting to z_{L0} = 320.0 mm. In this manner LLD amounting to $\Delta z = z_{R0} - z_{L0}$ = 10.5 mm is simulated. Response in the height of the left and right force plate is shown in Figure 9. As the right force plate is higher, the left force plate will measure a force greater that the one measured by the right force plate. Response of the measured force of the right and left force plate is shown in Figure 10. Thus, along the x axis CoM is displaced to the negative side. CoM displacement response along the x axis is shown in Figure 11. The values of CoM position along the x axis range between -46 and -44 mm. Postural sway is the reason why the CoM position does not have a constant value. At the moment t = 16 s manual compensation of the known LLD amount was initiated by means of GUI. The reference height of the left force plate amounting to 330.5 mm was given. During the compensation, the difference of the measured forces of the left and right force plate tends to 0

N (see Figure 10), and the position of CoM along the x axis tends to 0 mm (see Figure 11). The experiment has shown that LLD compensation may be performed by bringing the CoM position in the position $CoM_x \approx 0$. The inclination of the left and right force plate amounts to 0° and does not change during the change in height of the left force plate (see Figure 12). The operation of the system for compensating for LLD is shown on YouTube [15].

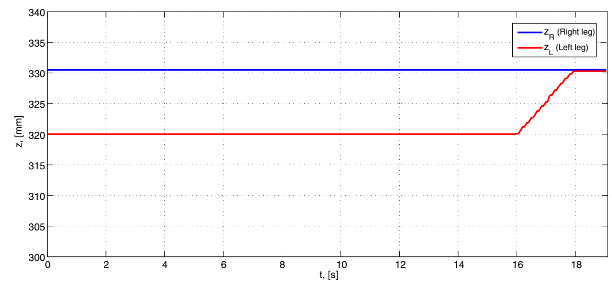


Fig. 9: Response in the height of the right and left force plate

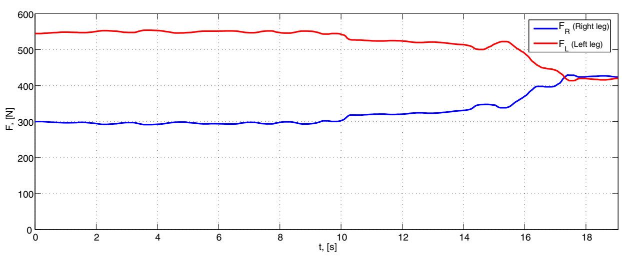


Fig. 10: Response of the measured force of the left and right force plate

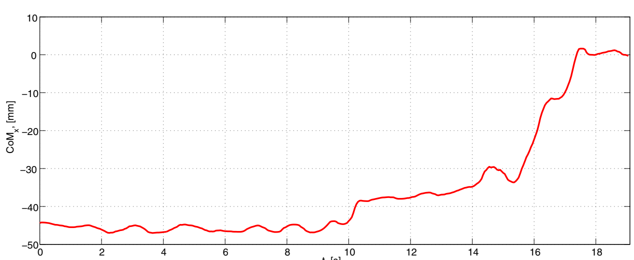


Fig. 11: CoM displacement response along the x axis

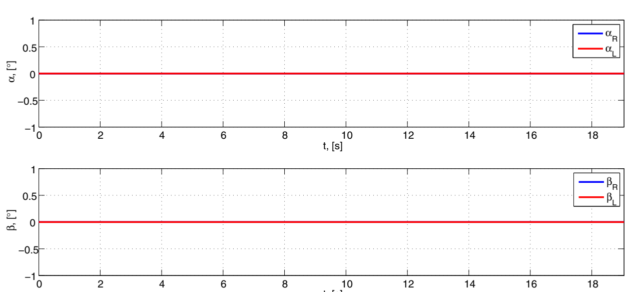


Fig. 12: Plate inclination: rotation around the x axis α [°] and rotation around the y axis β [°]

VI. Conclusion

This paper describes the system for compensating for LLD based on the estimation of the CoM of a human body. A prototype of the system for compensating for LLD was made. It includes two 3-RPS parallel manipulators with a moving force plate, control and measuring electronics and GUI. Experimental results indicate that LLD may be compensated for by balancing the human body, which sets CoM in the correct position. Future work on the system for compensating for LLD will include automated human body balancing using a visual feedback on standing at rest. It is necessary to reduce the effect of postural sway on the estimation of CoM position.

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