Half-Yearly Progress Report for Jan-May 2022

Data sheet for MS scholars

Name: Mowbray RV

Registration No.: ME20S042

Department: Mechanical

Date of Joining: 03/02/2021

Specialization / Stream: Design

Area of Research Work: Dynamics and control

Category of Admission: - GEN Sch - Regular - No

(Regular/Part Time / External/Project…): MS -NHTRA

Guide: Sourav Rakshit

Co-Guide(s) (if any): No

Dates of GTC Meetings:

Description	**Event**	**Date**
1st GTC Meeting	Progress review / Research proposal meeting (Within 18 months from the date of registration) (Mandatory)	
2nd GTC Meeting	Research seminar (Within 27 months from the date of registration) (Mandatory)	
3rd GTC meeting	Thesis submission meeting (within 30 months from the date of registration (Mandatory)	
Subsequent GTC meetings	Every 6 months till maximum period of the program or thesis submission whichever is earlier (Mandatory)	

Details of course work

S.No	Course No.	Course Title	Sem. (July-Nov or Jan.-May) and Year (20xx)	Credit	Grade
1	ID6020	Introduction of Research (Institute Module)	01(JAN-MAY 2021)	-	-
2	ME5203	Advanced Mechanics of Solids	01(JAN-MAY 2021)	9	A
3	ME5204	Finite Element Analysis	01(JAN-MAY 2021)	9	A
4	ME6226	Product Reliability	01(JAN-MAY 2021)	9	A
5	ID5020	Multi Body Dynamics & Applications	02(JUL-NOV 2021)	9	A
6	ME7223	Optimization Methods for Mechanical Design	02(JUL-NOV 2021)	9	B
7	ME6222	Design of Mechanical Transmission systems	03(JAN-MAY 2022)	9	B
		OVERALL CGPA			8.67

Mowbray RV

Signature of Scholar　　Signature of Co-Guide　　Signature of Guide

1 Short Summary

Title of research work:
Design, Development, and Testing of Gait Training Setup with Lower Limb Exoskeleton for Gait Training of Stroke and Spinal Cord Injury Patients.

Problem Definition / Research Objectives:
The rehabilitation process of gait training of stroke and spinal cord injury patients involve manual assisted walking on a treadmill with body weight. The process being completely done by a group of physiotherapists is tedious and impossible for longer sessions of training. The primary nature of the work proposed tries to overcome the odds faced in the manual process with a robotic lower limb exoskeleton for training. The focus is given on design, development of an indigenous low cost lower limb exoskeleton as a product for efficacy of rehabilitation in the country.

The research objectives can broadly listed into

1. Optimum design and fabrication of lower limb linkages with ergonomics and strength to assist the human leg.
2. Design and fabrication of body weight support with unique features that current market fails to address
3. Development of control system of the exoskeleton to assist the commands provide by an physiotherapist during the rehabilitation.
4. Selection of type of actuation based on design metric formulation with inputs from current physiotherapists.
5. Development of dynamics model of human gait with contact constraints.
6. Trajectory stabilization of the dynamics based for a reference input trajectory .

Research topic/gaps/tasks identified:

1. The primary task of imitating the human gait in the robotic exoskeleton with a model-based feedback control lies in developing its dynamics with high fidelity. However, the inherently complex nature of human gait makes the dynamics of the system hybrid, highly constrained and nonlinear. We investigate the framework of finding the multi-phase optimal control for the dynamics of a human gait having frictional contact, to track the reference trajectory with minimal deviation subjected to external perturbations. The trajectory stabilization control we have used is the LQ tracking. The formulation of the LQ tracking with contact considered makes it a constrained LQ tracking problem, increasing the complexity as the widely used method of dynamic programming stands invalid. In the upcoming part of the abstract, we explain how we obtain the contact formulation, the methodology used to solve and optimizing the design matrix for better tracking.

2. The exoskeleton unit consists of two lower limbs for each leg. The High torque motors for actuation of links are also mounted on them. The combined load increase the weight of the system and in turn the external torque compensation increases. To address the issues, we perform topology optimization of an external part being added in the other end for the net reduction in moment of inertia, this compensates the additional external torque requirement.

Summary of work done up to previous review:
Not applicable
Work done during the current review period:

1. Curve fitting of Fourier series for the gait trajectories based on the dataset from [1]

2. Development of dynamics model of gait of seven link biped with contact considered.

3. Inclusion of variable contact based on gait sequence and formulation of a hybrid contact constrained dynamic problem.

4. The complete design process was performed with weekly collaborative meeting with doctor and physiotherapists from Institute of Neurosciences- Kolkata to understand the real time problem faced.

5. Design iteration and manufacturing of lower limb exoskeleton.

6. Design of body weight support (BWST) with unique features that current market fails to address. The manufacturing of this unit is done in collaboration with the central workshop, IIT Madras. The raw material procurement and manufacturing process is in progress.

7. Optimization of BWST link length for minimization of eternal actuation effort.

8. Design of the spine support: The design involves a parallelogram mechanism with a gas spring and in the plane parallel to the back of the user a mechanism for lateral displacement and tilt of pelvic during the gait cycle is provided. Thus, this module in overall supports the pelvic tilt, lateral and vertical displacement during the entire gait cycle with free movable joints which induces a better ergonomics for the user.

9. Design and manufacturing of test rig for testing and learning the control of motor. The following parameters such as range of motion, load, ergonomics and safety will be tested.

Future work plan (at least for the next 6 months), as Gantt chart or similar chart:

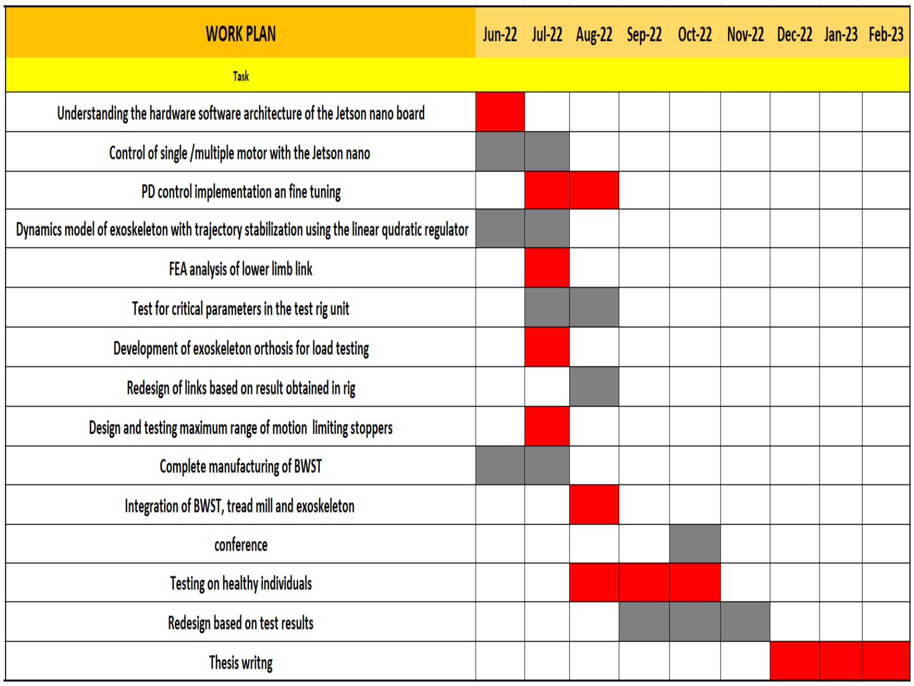


Figure 1: Timeline chart for next CAD design of the complete system.

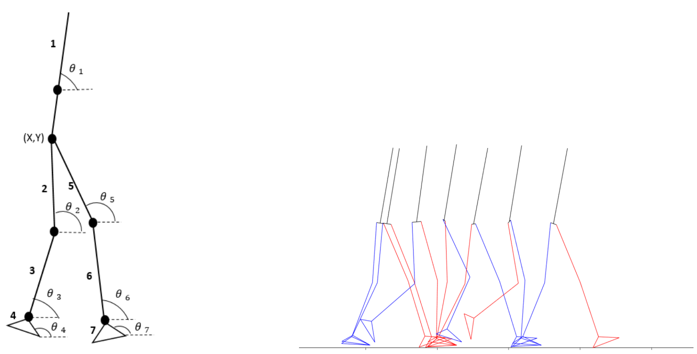
Visible research output

- Publications:
- Conferences:
  - Abstract accepted under the heading 'Optimal trajectory stabilization of lower limb exoskeleton involving hybrid contact dynamics' in the The 6th Joint International Conference on Multibody System Dynamics and the 10th Asian Conference on Multibody System Dynamics.
  - Abstract accepted under the heading 'A 2D Unified Gait Model for both single and double stances' in the The 6th Joint International Conference on Multibody System Dynamics and the 10th Asian Conference on Multibody System Dynamics.
- Workshops:

2 Detailed Report

2.1 Dynamics and control

The model developed has a kinematic topology of a 7-link Biped and nine degrees of freedom of the hip joint translation, torso orientation, right hip angle, right knee angle, right ankle angle, left hip angle, left knee angle, and left ankle angle as shown in Figure 2a). All joints are frictionless and revolute, and gait is over a straight horizontal terrain. During walking, the kinematics of the gait changes from open chain in Single support phase (SSP) to closed chain in Double support phase (DSP) as shown in Figure 2b), the Matlab simulation of human gait for one cycle, the red limb indicates the front leg and the blue limb indicates the rear leg. The contact established between the foot and the ground is subjected to changes based on the gait phase, so we distinguish the contact events from the start till the end of a gait cycle to obtain a predefined contact sequence as tabulated in Table 1. A clear illustration of hybrid contact events can also be noticed in Figure 2b). The gait starts with an initial heel contact on the front leg and flat foot contact for the rear leg, and on the transition to the next phase, the contact changes to flat foot contact on the front leg and toe-off in the rear leg, in a similar manner the contact sequence continues to achieve the walking gait. The Equation (1)



(a) (b)

Figure 2: a) Seven link Biped. b) Walking gait simulation.

to (3) gives the rigid body equation of motion subjected to an external contact involving friction [2]. Considering the contact constraints implicitly applied, the constrained dynamics is obtained in Equation (4), here $\beta(\mathbf{q},\dot{\mathbf{q}})$ is the contact Hessian and $\mathbf{C_T}(\mathbf{q})$ represents the contact Jacobian.

$$\mathbf{M}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{C}(\mathbf{q},\dot{\mathbf{q}})\dot{\mathbf{q}} + \mathbf{G}(\mathbf{q}) = \tau \tag{1}$$

$$\mathbf{g_n}(\mathbf{q}) = 0 \tag{2}$$

$$\mathbf{q_f}(\mathbf{q}) = 0 \tag{3}$$

$$\begin{bmatrix} \mathbf{M}(\mathbf{q}) & \mathbf{C_T}(\mathbf{q})^T \\ \mathbf{C_T}(\mathbf{q}) & 0 \end{bmatrix} \times \begin{bmatrix} \ddot{\mathbf{q}} \\ -\lambda \end{bmatrix} = \begin{bmatrix} -\mathbf{C}(\mathbf{q},\dot{\mathbf{q}})\dot{\mathbf{q}} - \mathbf{G}(\mathbf{q}) + \tau \\ \beta(\mathbf{q},\dot{\mathbf{q}}) \end{bmatrix} \qquad \text{for} \lambda \geq 0 \tag{4}$$

Table 1: Contact events in gait cycle

Numbering	Phases	Rear leg	Front leg
-	Initial start	Flat foot	Heel contact
1	DSP 1 sub-phase 1	Flat foot	Flat foot
2	DSP 1 sub-phase 2	Toe contact	Flat foot
3	R-SSP sub-phase 1	Mid swing	Flat foot
4	R-SSP sub-phase 2	Heel contact	Toe contact
5	DSP 2 sub-phase 1	Flat foot	Toe contact
6	L-SSP sub-phase 1	Flat foot	Mid swing
7	L-SSP sub-phase 2	Flat foot	Heel contact

The constraints in the Equation (4) will be updated for different phases based on the hybrid contact sequences leading to the switching of the equations for the respective phases[3]. Now, we formulate the optimal control problem using a Linear Quadratic Regulator for tracking the nominal trajectory for the dynamics defined in the Equation (4). The nominal trajectory is represented by ${x_t}^R$ for $t \in T$, is obtained from the OpenSim Gait 2354 model for different walking speed [4] and modified by a factor α_{us} depending on the user specifics.

$$V_N(\mathbf{x_t}, \mathbf{u_t}) = \min_u \frac{1}{2} \sum_{t=0}^{N-1} ((\mathbf{x_t} - \mathbf{x_t}^R)^T \mathbf{Q} (\mathbf{x_t} - \mathbf{x_t}^R) + \mathbf{u_t}^T \mathbf{R} \mathbf{u_t}) + \frac{1}{2} (\mathbf{x_N} - \mathbf{x_N}^R)^T \mathbf{P} (\mathbf{x_N} - \mathbf{x_N}^R) \tag{5}$$

The objective function of the trajectory stabilization is stated in the Equation (5), here $u \in \mathbb{R}^3$, $x \in \mathbb{R}^3$ represent the control input and states space at any given time t , $\mathbf{P}$ is the terminal cost matrix and the matrices Q and R represent the penalty cost on the trajectory deviation and control input. The objective function is taken as a minimization problem of the weighted sum of the state error, and the control input, as shown in the Equation (5) and is subjected to the constrained dynamics in the discretised state space form. Thus our trajectory stabilization formulation becomes a constrained LQ tracking problem. The constraint arises as in our case, the Equation (5) is not only subjected to the linear dynamics in discrete form but also subjected to a linear equality constraint. The Equation (5) and The Equation (4) is the formulation of the LQ tracking for the hybrid contact dynamics defined.

The formalization we state looses its recursive nature, so we cant solve it with the standard Algebraic Riccati Differential Equation. So, we solve our formalization using the nonlinear equality constrained programming technique and the optimization problem takes the form of a QP. Further, for the problem stated the R matrix with weighted diagonal elements is considered non-uniform to find the best penalty for each element of the control input.

2.2 Design

The design of the system depicted in figure 3 consists of four major entities

1. Lower limb exoskeleton linkages
2. Body weight support
3. Support module
4. Treadmill

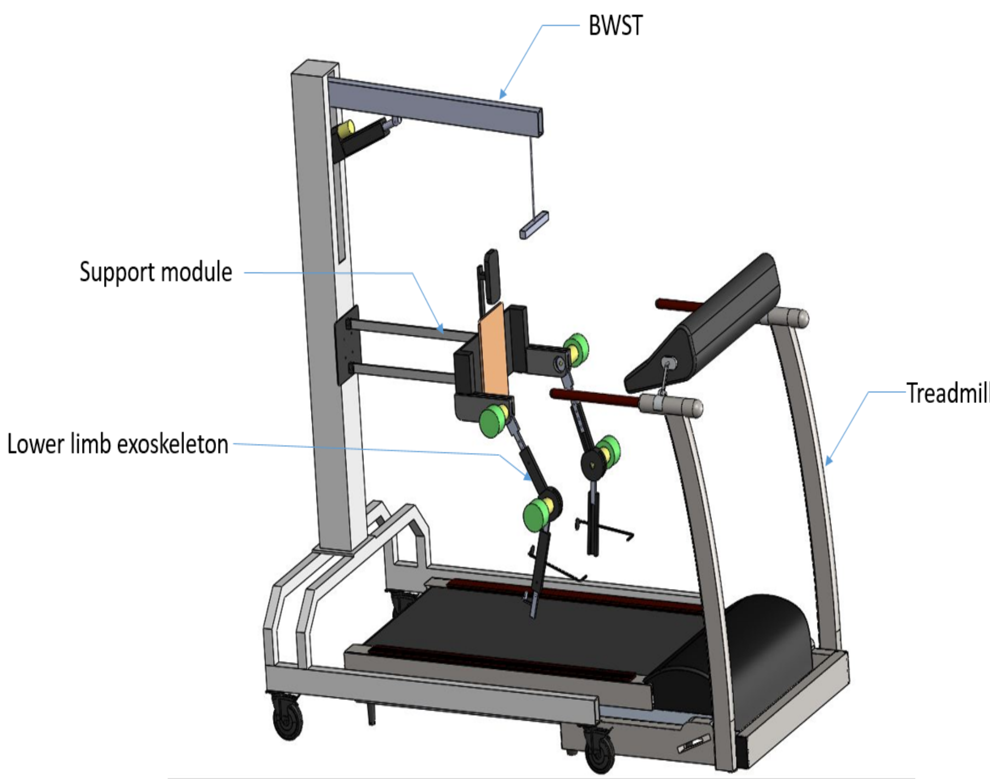


Figure 3: CAD design of the complete system.

The exoskeleton consists of linkages for both limbs. The linkages assist the thigh and leg of the user during the gait training, providing the actuation that the user fails to provide. The unit consists of two heavy torque motors for each limb. The motor placement coincides with the hip and knee joint of the user and aids the flexion and extension of the knee and hip. The heavy torque motors mentioned are servo motors, and their selection is purely based on the dynamic results from [5] and inputs from physiotherapists. The linkages are also designed to have a variable-length for accommodating users with different limb lengths.

In the exoskeleton, the active actuation is limited to the sagittal plane of movement and the minor movements are taken care of by the passive joints in the spine support module. The spine support module depicted in figure 3 provides free movement for pelvic tilt, lateral and vertical displacement.

Further, the BWST helps to reach the patients outside the workspace of the exoskeleton and carries them with the help of a jacket being attached. And it coordinates the patients to synchronous with the exoskeleton and the treadmill below. The design of the BWST depicted in figure 4 address the unique feature that the market product lacks such as

- Telescopic horizontal extension
- Rotation of top column for a pickup reach range for patients from -90° to 90°.
- Adjustable body weight support load carrying feature

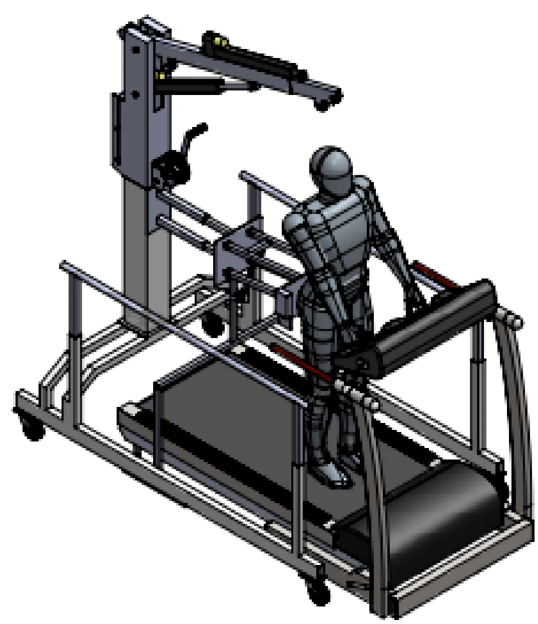


Figure 4: Final BWST CAD design.

2.3 Control unit

The control of the exoskeleton unit involves reproducing the predefined gait trajectory for the stroke and spinal cord injury patients attached to the unit. The task stated requires the system to control the links to a trajectory despite the external load of the user. Other variable factors such as different kinematic length of the patient and weight of the patient should not also affect the control system performance.
For the exoskeleton designed we are using the PD control for each motor. The motor control sequence and implementation of the PD control is performed with the Jetson nano development board.

2.4 Testing

Testing the exoskeleton setup for the proper working of its control system is an essential step as the final aim of the product is to couple the unit with a user. A failure in the system directly impacts the user. Before directly testing the system with the user, we have developed a test rig design depicted in 5 and figure 6, where similar external dynamics will be subjected to it. The test values recorded are given a proper tabulation for further design synthesis. The following test is being performed.
The following test is being performed

- How close the links follow the predefined trajectory.
- Performance on variable external loads using a in house developed exoskeleton orthosis.
- How well its operation limits in the maximum range of motion(ROM)
- Testing the sudden braking of system
- Testing the ROM limiting mechanical stoppers performance
- Testing of power overshooting in extreme load work conditions

The test rig is constructed in real time as depicted in figure 7 and figure 8.The testing process is currently being performed.

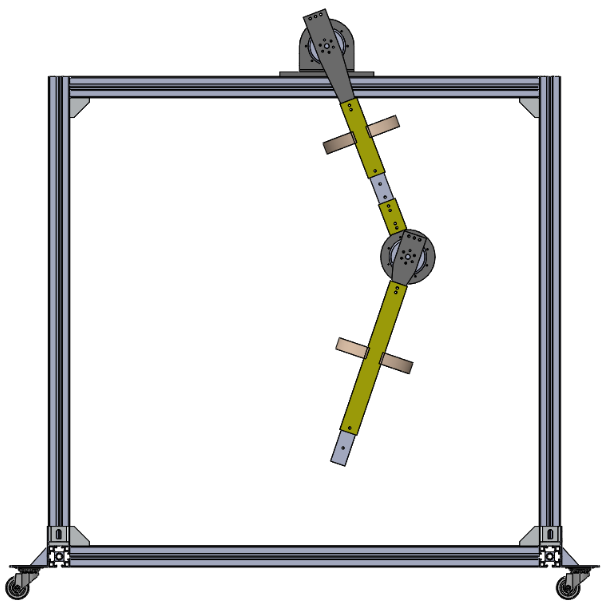


Figure 5: Side view of test rig CAD design.

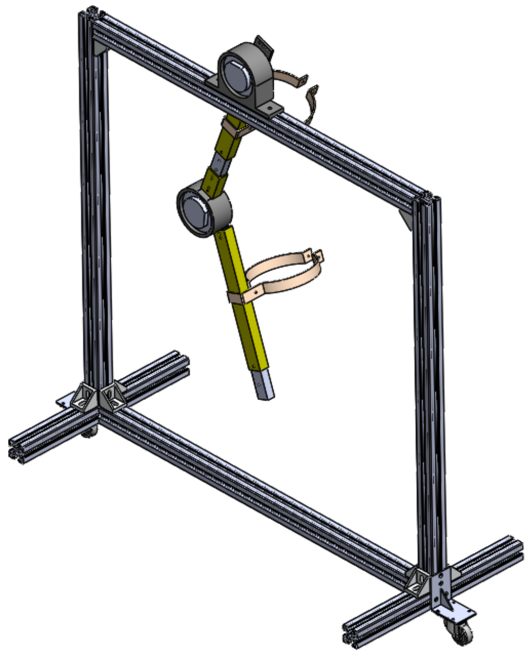


Figure 6: Isometric view of test rig CAD design.

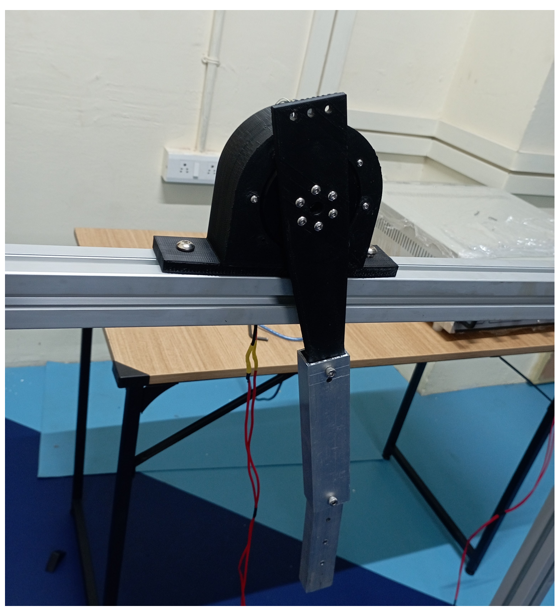


Figure 7: T motor AK 80-64 mounted with the links.

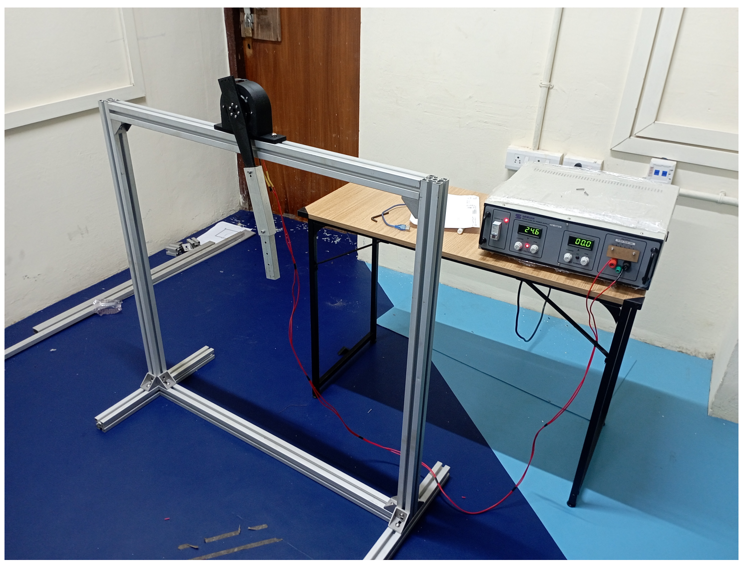


Figure 8: Test rig built in the GAMMA lab of MDS.

References

[1] F Schreiber, C Moissenet. A multimodal dataset of human gait at different walking speeds established on injury-free adult participants.), (2019.

[2] A.A Shabana. Computational Dynamics (3 edition)), 2014.

[3] A.Rodriguez F.R Hogan. Feedback control of the pusher-slider system: A story of hybrid and underactuated contact dynamics, 2016.

[4] S.L Delp C.T John, A.seth M.H Schwartz. Contributions of muscles to mediolateral ground reaction force over a range of walking speeds. Journal of Biomechanics. *Journal of Biomechanics*, 45:2438–2443, 2012.

[5] D. A Winter. Biomechanics and Motor Control of Human Movement (4th ed.), 2009.