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Study on the Design and Analysis of a 4-DOF Robot for Trunk Rehabilitation

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체간 재활을 위한 4-DOF 로봇의 설계 및 분석에 관한 연구

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ABSTRACT

This paper presents the development of a robotic system for rehabilitation of the trunk's ability to maintain postural control under different balance conditions. The system, developed with extensive input from rehabilitation and biomedical engineering experts, consists of a seat mounted on a robotic mechanism capable of moving it with four degrees of freedom (3 rotational and 1 translational). The seat surface has built in instrumentation to gauge the movements of the user's center of pressure (COP) and it can be moved either to track the movements of the COP or according to operator given commands. The system allows two types of leg support. A ground mounted footrest allows participation of legs in postural control while a seat connected footrest constrains the leg movement and limits their involvement in postural control. The design evolution over several prototypes is presented and computer aided structural analysis is used to determine the feasibility of the designed components. The system is pilot tested by a stroke patient and is determined to have potential for use as a trunk rehabilitation tool. Future works involve more detailed studies to evaluate the effects of using this system and to determine its efficacy as a rehabilitation tool.

Keywords : Trunk Rehabilitation(체간 재활), Core Stability(코어 안정성), Robotics(로봇 공학), Center of Pressure(COP)(압력중심), Stroke Patient(뇌졸중 환자), Sitting Balanc(앉기 균형)

1. Introduction

The muscles making up the human core need to work synergistically to stabilize the skeletal structure including the spine and the pelvis to form the stable kinetic chain necessary for safe motion of the body[1]. These muscles ensure maximum force generation during the performance of tasks, while also ensuring that a well distributed minimum amount of force is exerted on the joints[2]. Core stability refers to the ability of the core to resist buckling and to return to a stable state after perturbation[3]. Neuromuscular

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ailments such as stroke can adversely affect the functioning of the core, thus degrading core stability. Stroke can have lasting effects including sensory, motor, cognitive and emotional impairments. The ability to safely and independently perform gait and the activities of daily living (ADL) is reduced by these impairments[4-12]. The performance of trunk rehabilitation exercises can improve trunk control, sitting and standing balance and patient mobility[13]. Such exercises have also been shown to improve the gait speed, cadence, and static and dynamic balance of stroke survivors[14-16]. Therefore, the initial rehabilitation of trunk control is recommended for stroke patients to pave the way for recovery of other functions[17].

The control of seated posture can be divided into three types, i.e. static, dynamic and reactive postural control[18]. The seated balance rehabilitation protocols are usually designed according to the particular type of postural control that is to be improved. Generally, the rehabilitation protocol starts with easier exercises and once the patient has sufficiently mastered them, the difficulty level is increased[18]. At the basic level, the patient sits on a stable firm surface with hips and knees flexed at 90 degrees and feet set hip-width apart, and performs the rehabilitation exercise. The difficulty level can be set by modifying the base of support (hands on thighs or across the chest, feet on ground or suspended), modifying the support surface (stable or unstable surface), and/or modifying the sensory input (eyes open or closed). Once a patient is able to satisfactorily maintain their static and dynamic balance, their reactive postural control can be challenged through forced perturbations of their balance. Patients requiring additional assistive input can be provided augmented feedback for guidance and for improvement of focus. Augmented visual feedback of the body's center of pressure (COP) has been shown to positively influence the sitting balance of patients in the chronic stage of recovery after stroke[19].

The execution of sitting balance rehabilitation protocols can add to therapist workload and fatigue as it requires the extensive involvement of one or more therapists. The use of a robotic rehabilitation system may be helpful for the therapists in this regard. Other aspects of sensorimotor rehabilitation have been shown to have benefitted from the use of robotic systems[20]. Similarly, sitting balance rehabilitation can also be benefited by the use of robotic systems that can generate different exercise scenarios, provide augmented feedback and continuous monitoring of balance indicators such as the COP position. With this perspective, some such systems have been developed[21,22]. The most notable such system is the Hunova developed by Movendo Inc.[22]. This system has instrumented seating and footrest platforms that determine the position of the user's COP and move to track its movements. These surfaces have a stiffness field that continually pushes them back to their neutral positions. The movement of the footrest inhibits the amount of support and sensory feedback that the user can get from their lower extremities (LE). However, the complete removal of LE proprioceptive input may not be possible with this system as the joints (especially the ankles) still retain a certain degree of movement because of their being a separation between the seat and footrest axes of rotation.

If the LE support and proprioceptive feedback is removed, the sensory, control and majority of the force generation all have to be performed by the trunk[18,23]. In order to do this, either the LE need to be suspended freely without any support[18], or they must be constrained to move with the pelvis so that there is no movement of the joints as the pelvis is rotated[23]. Since the free suspension of LE when the person is sitting on a robotic moving seat can be unsafe, having a footrest structure that moves the LE with the seat surface is preferable. With all these factors in mind, in this paper we present the development of a trunk rehabilitation robot. The developed system consists of a seat mounted on a robotic mechanism capable of moving it with four degrees of freedom (3 rotational and 1 translational). The seat surface has built in instrumentation to gauge the movements of the user's COP. The seat can be moved either to track the movements of the COP or according to operator given commands. The system incorporates two LE support configurations; a ground mounted footrest to allow LE participation in postural control and a seat connected footrest to constrain the feet so that they have no motion relative to the pelvis. The latter configuration can be used to put the bulk of the responsibility for postural control on the trunk. The type of footrest used can be selected according to the protocol being implemented. The system is equipped with a screen for providing visual feedback of the user's COP. We have also developed a number if graphical interfaces to allow for the performance of different rehabilitation exercises[24]. This paper presents the design evolution of this system and provides details of its latest design. The designs have been evaluated based on expert opinions, computer simulations, and a pilot user study, the results of which are also presented here.

2. System Design

2.1 Design Concept

The system is designed so that the user can sit on the instrumented seat surface and perform the rehabilitation exercises, which will usually involve them controlling the position of their COP to try and reach goals that appear on the screen. The seat surface can be used in one of three conditions, i.e. static, unstable or forced perturbation. The static seat provides a stable base of support similar to a conventional chair. The unstable base of support is generated by having the seat move to track the user's COP. Forced perturbations are generated by having the seat move according to the operator's commands irrespective of the position of the user's COP. The system is designed to comfortably accommodate Korean citizens aged 30 to 69 years[25], weighing up to 135 kg. The system has three rotational degrees of freedom; roll, pitch and yaw. The roll movement corresponds to the Medio-Lateral (ML) direction while the pitch movement corresponds to the Antero-Posterior (AP) direction of the user's movements. The pitch movement has a greater range of motion to the front that when combined with the heave movement can provide assistance in sit-to stand transitions. The heave movement also enables setting of the seat height to maintain the proper limb geometry; knees and hips flexed at 90 degrees[18]. The yaw movement mainly provides for ease of boarding for wheelchair bound users. The ranges of motion of all these movements are given in Table 1.

Table 1 System ranges of motion

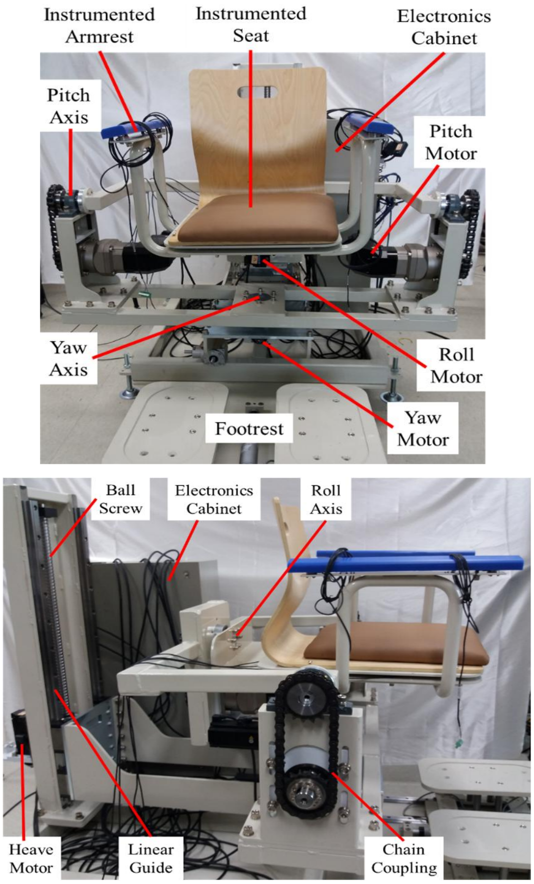
Movement	Range
Roll	±15º
Pitch	-15º to +45º
Yaw	±45º
Heave	0 to 450mm

2.2 Design Evolution

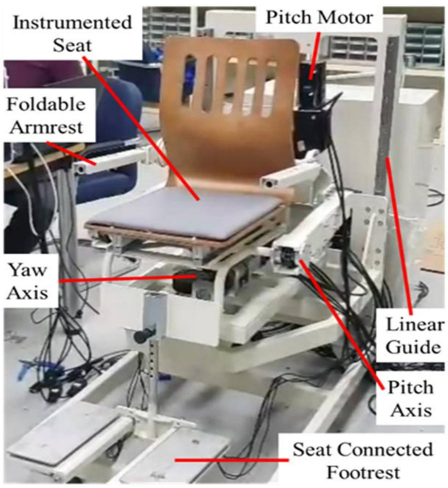
Based on the previously mentioned design concept, we designed and manufactured the prototype robotic system shown in Fig. 1(a). We performed a functional assessment of the system[24] and presented it to a focus group composed of rehabilitation and biomedical engineering experts. The experts agreed that the system concept is useful and the system may be beneficial for rehabilitation of persons with sensorimotor deficits of the core.

However, they were of the view that the system was too large and thus was not 'inviting' for the users. The excessive bulk of the system also posed serious controllability issues, especially at the extremes of the movement ranges.

Based on the observations from the first prototype,



(a) The first system prototype



(b) The second system prototype

Fig. 1 Previously developed system prototypes

we developed a second prototype having a relatively compact structural design, shown in Fig. 1(b). This design was appreciated by the experts and it also did away with the controllability issues faced with the previous design. However, during pilot tests with a healthy user, it was observed that the system flexed noticeably. This caused the user to feel as if they were bouncing on a springboard. We observed that each part of the robot only flexed a little. But, since it is a serial type system, these deformations added up and resulted in much larger oscillations of the seat surface. In order to solve these problems, we designed a new version of the system. In order to evaluate the new design, we undertook the study reported in this article. In this study we utilized finite element method (FEM) based software analysis to determine the deformations occurring in the second prototype design and the new design. We compared these deformations to determine feasibility of manufacturing the new design. Once the design was deemed feasible, we manufactured the prototype and carried out usability tests with a person recovering from stroke.

2.3 Design Details

The system can be divided into two major parts; the COP sensing part and the robotic movement part. The COP sensing part consists of four compression load cells placed one at each corner of the seat. The load cells are sandwiched between two rigid plates. The plate at the top is used as the seat surface while the one at the bottom is connected to the system structure.

The load cells are interfaced with indicators that filter and digitize the load cell outputs and transmit them to a personal computer (PC) via RS-485 interface. The PC is equipped with a serial port extension card to allow communication with multiple indicators at the same time. A software running in the LabView development environment (LabView 2015, National Instruments) filters the data using a low

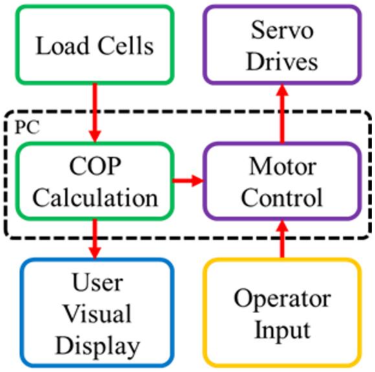


Fig. 2 System block diagram

pass filter and calculates the position of the user's COP referred to the center of the seat surface. The COP position is calculated using equations (1) and (2) where, and are the forces measured by the four load cells, and L and W are the length (along X axis) and width (along Y axis) of the seat surface, respectively. This COP position is used to generate the visual feedback and is also communicated to the motor control software. The visual feedback and motor control software both run on the same PC in the same environment. The data flow between the different system modules is shown in Fig. 2.

$$X_{COP}=\frac{(F_1+F_2-F_3-F_4)\times\left(\frac{L}{2}\right)}{F_1+F_2+F_3+F_4} \quad (1)$$

$$Y_{COP}=\frac{(F_2+F_3-F_1-F_4)\times\left(\frac{W}{2}\right)}{F_1+F_2+F_3+F_4} \quad (2)$$

The motor control software runs the motors either according to the operator's commands or according to the admittance control scheme that works to track the COP position. Details of the control scheme are given in the next section. A motor controller card installed in the PC sends the drive commands generated by the software to the motors using a MECHATROLINK III interface. The third system prototype, shown in Fig. 3, employs a total of five AC servo motors.

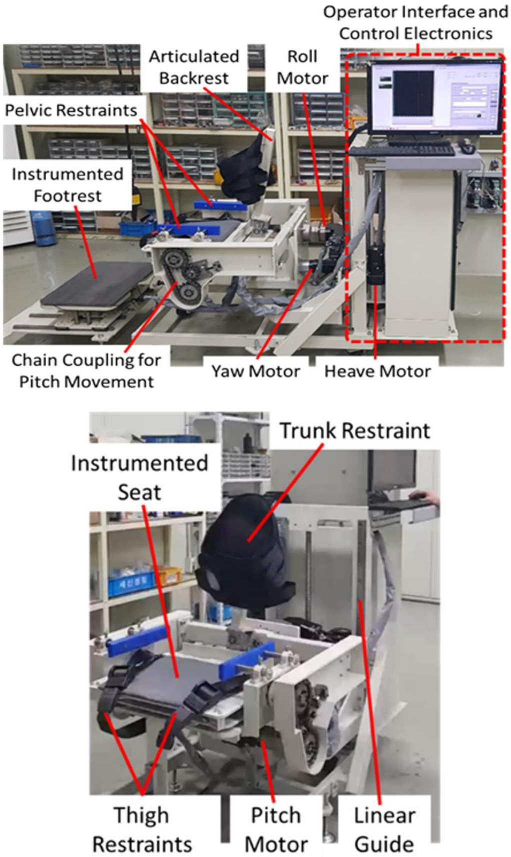


Fig. 3 The third system prototype

There are two motors used to actuate the pitch movement, while one motor each actuates the roll, yaw and heave movements. The roll, pitch and yaw motors have attached gearheads to obtain the required amount of torque, while the heave motor does not use any gearing. The pitch gearhead output shafts are coupled with the pitch shaft of the system through a chain sprocket assembly with 1:1 ratio. The roll gearhead is coupled directly to the roll shaft. The yaw movement is driven by the actuation assembly through a worm gear arrangement. The heave motor is connected to a ball screw arrangement via a toothed belt. The system structure that is required to move in the vertical direction is attached to the nut of the screw assembly and rides on two linear guides.

Table 2 Details of system components

Component	Description	Qty.
Load cell	CBFSB-100kgf, Bongshin	4
Indicator	BS-105, Bongshin	4
Serial port extension card	PCIE 1622C, Advantech	1
Motor controller card	MP3100, Yaskawa	1
Remote I/O module	R7K4FML3-6-DAC32A, M-System	1
Pitch motor	SGM7J-04A7D2C, 400 Watt, Yaskawa	2
Pitch motor gearhead	KSFL-100-120-P1, 1:120, Liming ATG	2
Roll motor	SGM7J-04A7D2C, 400 Watt, Yaskawa	1
Roll motor gearhead	KSF-100-80-P1, 1:80, Liming ATG	1
Yaw motor	SGM7J-02A7D2C, 200 Watt, Yaskawa	1
Yaw motor gearhead	PGX62-H-40, 1:40, Liming ATG	1
Heave motor	SGM7J-08A7D2C, 750 Watt, Yaskawa	1

All the motors have electronically actuated mechanical brakes that are controlled using a remote I/O module that is connected to the PC through the same MECHATROLINK III interface. The system has been designed so that the rotational axes intersect at the center of the top surface of the seat. The details of the hardware components used in this system are given in Table 2.

2.4 Control System

The system utilizes the admittance control methodology to move the seat so that it tracks the position of the COP. Fig. 4 shows the block diagram of the control system where $COP_d \in R^2$ is the desired COP position and $COP_{measure} \in R^2$ is the current COP position from equations (1) and (2).

The admittance $1/Z(s) \in R^{2\times 2}$, is the diagonal matrix used to generate the system angular velocity control command, v_d. On order to accomplish low-level motor control, the feedback angular velocity $(\dot{\theta}_m)$ is fed to the PI_{speed} controller that is tasked with following the velocity control command generated by the admittance block. The admittance block is defined as,

$$\frac{1}{Z(s)} = \begin{bmatrix} \frac{1}{I_x s + b_x} & 0 \\ 0 & \frac{1}{I_y s + b_y} \end{bmatrix} \tag{3}$$

Where, I_x and I_y are the virtual inertia, and b_x and b_y are the virtual damping coefficients. These coefficients can be tuned according to the inertia of the user's trunk in order to adjust the apparent instability of the system that is felt by the user.

3. System Evaluation

3.1 Structural Analysis

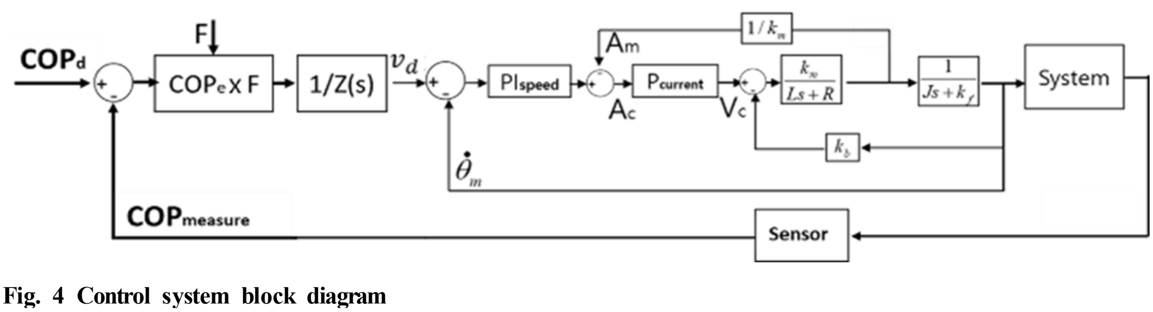
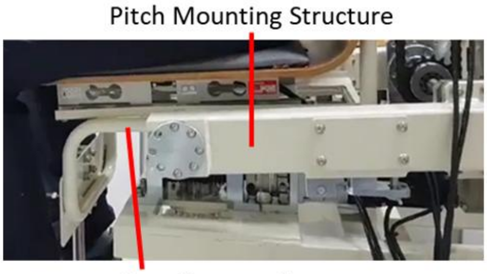
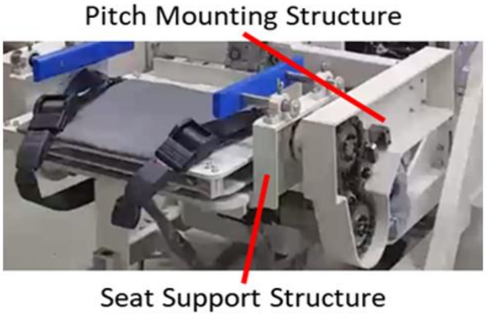


Fig. 4 Control system block diagram



(a) Analyzed components of the second prototype

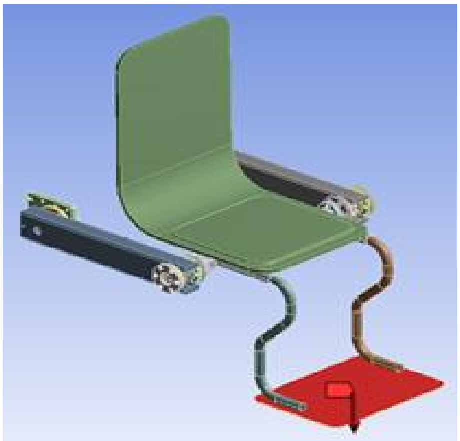


(b) Analyzed components of the third prototype

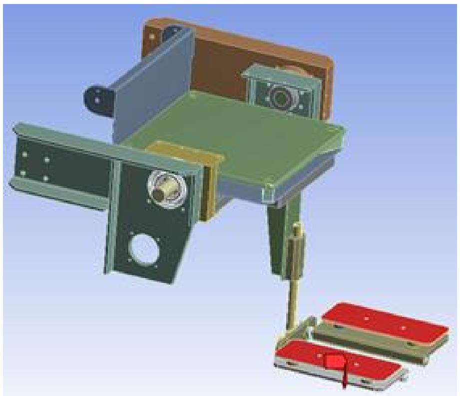
Fig. 5 Appearance of the components subjected to structural analysis

As mentioned above, the second system prototype suffered due to flexion of structural components.

Therefore, we performed a computer aided structural analysis of the second prototype to determine the deformations taking place in the key structural components. The newly designed components of the third prototype were also subjected to the same analysis. The deformations of these new components were compared with those of the second prototype. The analysis was done considering the case that almost all of a user's body mass is applied to the seat connected footrest. According to this loading condition and due to the geometry of the system design, we determined that the components having the highest amount of deformation would be the seat support structure and the Pitch mounting structure (shown in Fig. 5). Therefore, the deformations occurring in these components under the action of the applied loads were analyzed using a FEM based software (ANSYS R18.2).



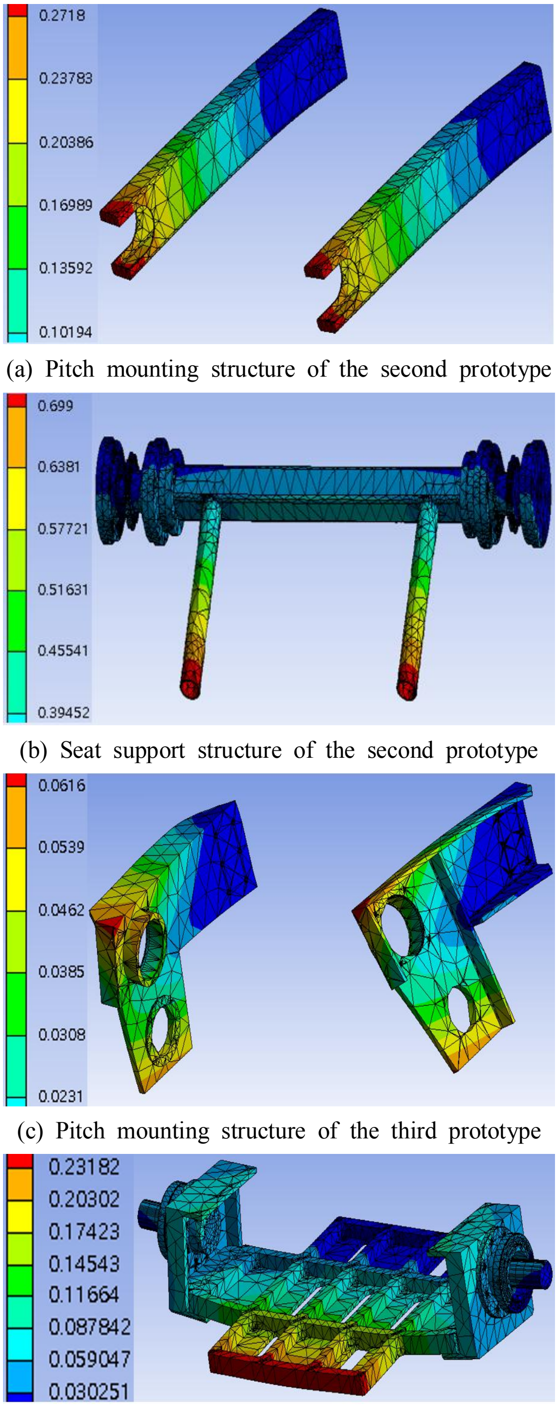
(a) Load applied on the second prototype



(b) Load applied on the third prototype

Fig. 6 The load applied during structural analysis on both the prototypes. The load is evenly distributed over the red colored surfaces

For both the analyses, the procedure adopted was the same. The system 3D models were loaded in the software and meshed using the default element size of 7.2522×10^{-2} m. All the joints were considered to be rigidly fixed. Then a 1,247 N distributed load acting vertically downwards was applied to the connected footrests, as shown in Fig. 6. The components are manufactured using structural steel so the appropriate material properties were set in the



(a) Pitch mounting structure of the second prototype

(b) Seat support structure of the second prototype

(c) Pitch mounting structure of the third prototype

(d) Seat support structure of the third prototype

Fig. 7 Component deformations due to applied load

software (Young's modulus: $2x10^{11}$ Pa, Poisson's ratio: 0.3, Bulk modulus: $1.6667x10^{11}$ Pa, Shear modulus: $7.6923x10^{10}$ Pa).

The total deformations that occurred due to the action of these loads are shown in Fig. 7. As can be seen in Fig. 7(a), for the pitch mounting structure of the second prototype the maximum deformation occurred at the ends of the arms that are attached to the pitch axis. While for the seat support structure, as shown in Fig. 7(b), the maximum deformation occurred at the members that extend out to connect with the connected footrest.

Based on these observations, in the third prototype, these components were designed to have substantially greater amount of material and the structure was designed so that downward acting stresses are borne by the larger aspects of the structure.

The deformations occurring in the third prototype components under the same test conditions are shown in Fig. 7(c) and (d). As can be seen, although the locations of maximum deformations are similar, the magnitude of deformation has been significantly reduced. For the pitch mounting component, the deformation reduced from 0.30577mm to 0.0693mm, which is a reduction of more than 77%. For the seat support structure, the deformation reduced from 0.7599mm to 0.26061mm, which is a reduction of more than 65%. With these results, the new component designs are considered appropriate for use.

3.2 User Study

The usability of the third system prototype (shown in Fig. 3) was evaluated through pilot testing with a person recovering from stroke (shown in Fig. 8). The study participant was a male in his 40s who suffered from right side hemiplegia due to a hemorrhage in the left side of the brain. He also suffered from desensitization due to diabetes but was able to walk with assistance.

During testing, the subject utilized the system in the unstable mode to perform a weight shifting exercise

Fig. 8 A stroke patient using the system during its pilot evaluation

where he was asked to shift his bodyweight to the right and left, and front and back, alternately. During the exercise and after completion, the subject gave his feedback about his experience and about the usability of the system. Physical therapy specialists also observed the system during testing and gave their feedback about its usability.

The subject performed the exercise for a total of 15 minutes, after which he was visibly sweating. This signifies increased energy use that may point towards increased use of the trunk muscles. This may lead to strengthening of the muscles through use of the system. The subject also reported being able to feel which of his muscles were weaker than the rest. This points to sensory stimulation of areas that otherwise have impaired sensitivity. With regards to the comfort of using the system, the subject felt that the seat needs to be more comfortable, armrests should be provided, and the backwards movement of the removable backrest should be limited. He also expressed the desire to have buttons on the armrests to allow him to position the seat as he desired.

The therapists shared the test subject's opinion to some extent. They also observed that the operator interface was difficult to understand and complicated to use due to having a non-intuitive control layout and the use of engineering related technical language.

4. Conclusion

The presented system has been designed with the extensive input from rehabilitation and biomedical engineering experts, and the design has evolved based on their feedback and mechanical requirements. The mechanical concerns regarding system stiffness were addressed using computer aided analysis and the outcomes have been evaluated using pilot testing with a stroke patient. Based on the observations gathered from the patient and the therapists, the system has been determined to potential for use as a trunk posture rehabilitation tool. There are still minor issues related to the comfort and ease of use of the system. In the future, these issues will be fixed and the system will be tested to evaluate its effects on the users' balance and muscle activation. Trials of the system with stroke patients to determine its efficacy as a rehabilitation tool will also be conducted as part of future work.

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