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The Design of a Novel Tilt Seat for Inversion Therapy

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ABSTRACT

Inversion therapy has attracted the attention for its application, in combination to rehabilitation therapy, to the treatment of back pain. Several tilt tables have been designed and commercialized for this scope, either motorized or gravitational. In this paper we present the mechatronic design and prototype of a novel tilt seat to be used for inversion therapy. The proposed device shows substantial improvements with respect conventional available tilt tables. It is actuated and controlled and is capable to perform static and intermittent inversion for any inclination defined by the end-user. The seat unit can be rocket forwardly and backwardly with full rotation of 360 degrees. Furthermore, the upright and inverted configurations are much more comfortable than those obtained with conventional tilt tables. In this paper a control scheme and numerical and experimental tests of the system are also shown.

Keywords: Mechatronics, Mechanical Design, Tilt Table, Inversion Therapy, Simulation.

Mathematics Subject Classification: 93C85, 93C95

Computing Classification System: I J.6, G.4

1. INTRODUCTION

In recent years, Robotics and Mechatronics were successfully applied in the Biomedical field. In particular, robotized rehabilitation devices can provide several advantages over traditional therapy, including objective measurements of the time-course of changes in motor control of limbs, and semi-autonomous practice of therapeutic exercises. Furthermore, they may lead to regular and repetitive exercises, which can be also planned and controlled; and give the possibility to customize therapies and exercises to meet the needs of patients. In addition, they can be designed according to the specific motion required, as reported in (Figliolini et al., 2012a and b) in which kinematic analysis and synthesis are proposed for planar and spatial mechanisms. Robotic systems can be then used to aid automate and repetitive training in a controlled way, and to increase treatment compliance by introducing incentives to a patient, such as games or performance-related scores (Rosati et al., 2009). In addition, the use of Robotics and Mechatronics in rehabilitation gives the possibility to reduce the costs of therapies, since a consistent number of pre-programmed exercises can be performed at home with suitable mechanical devices and even without the need of nurses or medical personnel.

Over the last few decades, domestic and service systems have become increasingly accessible and accepted. Despite early work showing the positive feasibility of assistive robotics and the high estimates of future markets (Mahoney, 1997), such systems seemed to be under-developed and have not sold well. Considering the wealth of robotic technology available, this lack of penetration into the user market seems paradoxical, as it appears to offer great promise for solutions in the assistive field. Therefore, there is the need of developing novel mechatronic and robotic systems that can be accepted by end-users and possess favorable characteristics such as easy-in-use and accessible or rather low-cost (Ottaviano, 2008). Several robotic systems have been designed specifically for medical applications (Gherman et al., 2012; Pisla et al., 2012), and for the rehabilitation of upper and lower limbs. Examples of such systems are: PAMM, which is a cane-based configuration with a skid-steer (non holonomic) drive (Dubowsky et al., 2000); ARMin, which is a robot for arm therapy applicable to the training of activities of daily living in clinics (Nef and Riener, 2005) and cable systems for the limb rehabilitation (Castelli and Ottaviano, 2010).

In this paper we propose a completely novel mechatronic design and a first prototype of a tilt seat that can be used for inversion therapy. Particular attention has been devoted to the mechanical design to reduce the production costs and to the control design being the system directed to generic end-users not medical personnel or nurses.

Back pain is a quite common problem in our industrialized world that may cause severe disease, as pointed out in (Bigos at al., 1994). In particular, conventional treatments for the degenerative lumbar disease deal with restriction of daily-life activity, bed rest, physiotherapy, rehabilitation, traction, surgery. All these treatments can be used alone and have been tested even in combination (Van Tulder et al., 1997). Rehabilitation can be also performed with the aid of robotic devices, as proposed in (Kawchuk et al, 2010).

Traction is a treatment for lumbar discogenic disease, which consist of separating vertebral bodies, distraction and gliding of facet joints, widening of the intervertebral foramen, straightening of the spinal curves and stretching of the spinal musculature (Harte et al., 2005), by a manual, mechanical or motorized operation. When the traction is operated by the weight of the entire upper half of the patient’s body assisted by gravity, the process of being upside down is known as inversion therapy. Usually, an end-user can be suspended by his/her ankles (or by lower articulation) and inverts his/her body configuration by moving backward the arms (in this case the device is called gravitational tilt table) or thanks to a motorized device.

Inversion therapy can be used not only to reduce back pain, but also for stretching and strengthening, because muscles such as the rectus abdominus and obliques are involved in the movement. There are two types of inversion that can be performed, namely static and intermittent inversion. The first type can be assumed as a stretching exercise. It is performed by choosing a tilting angle, which can be kept for few minutes. Gravity acts to pull on muscles for stretching the spinal column to relieve pressure on the vertebrae and the nerve roots (Bigos at al., 1994). This is one way to achieve spinal traction reducing the back pain. On the contrary, intermittent inversion is characterized by an intermittent rocking motion between upright and inverted configuration with a duration of 20 or 30 seconds for each cycle. This kind of exercise can bring fresh blood to the spine (Bigos at al., 1994).

Pioneer studies of inversion therapy were developed in (Sheffield, 1964), who reported that the 89 % of treated patients had significant improvements in the use of an inversion table. The conclusion of his work was that potential benefits of the therapy were related to the stretching of paraspinal vertebral muscles and ligaments and widening of intervertebral discs. His work found significant improvements in a number of diagnosis including spondylolisthesis, herniated discs, lumbar osteoarthritis with sciatica, and coccygodynia. Similar results can be found in other works (Ballantyne et al., 1986; Nosse, 1978). Moreover, a number of studies demonstrated the usefulness of inversion therapy over simple mechanical traction (Meshino, 1984). Physiological effects were investigated in (Vernon, 1985) and reported positive effects on normal subjects, whereas in (Clarke et al., 2007) it is reported that there is no proof of benefits of inversion. On the other side, recent results reported in (Prasad et al., 2012) show that intermittent traction with an inversion device can give a significant reduction in the need for surgery procedure.

In this paper the mechatronic design of a tilt seat is proposed and numerical results are shown, together with the first prototype of the system that can be used for inversion therapy.

2. MECHATRONIC DESIGN OF A NOVEL TILT SEAT FOR INVERSION THERAPY

The device proposed in this paper is capable to perform either static and intermittent inversion. It is based on a motorized tilting seat, which can be directly controlled by the end-user, in manual mode, alternatively the device can be pre-programmed by using an off-line mode.

Figure 1 shows the mechatronic design of the system, which is composed by a mechanical part (the novel tilt seat for inversion) together with its actuation and control units. In particular, the novel tilt seat proposed in this paper is composed by a seat unit 2), which is mounted on a fixed frame 1) capable of supporting in a stable way the entire structure and the end-user body weight during the inversion. In particular, the end-user can lift and accommodate on the device by using a step 6) that can be removed just after. The user can operate directly on the system by handlebars 4), which have suitable control buttons 5) for regulating clockwise and counterclockwise rotations of the seat about the so called main shaft. Handlebars are also useful for giving a stable configuration of the user and let him/her be more comfortable from upright to inverted configuration and backward. Moreover, handlebars can be used for safety reasons. The lap belt 3) when fastened engages the end-user by her/his upper side of the tights. When the seat is inverted the weight of the head plus the torso is supported by the lap belt on the tights, therefore, the spine is subjected to traction. Because of the angle between the seat and the back rest portions, and further action of the lap belt, the weight of the head and torso is equally supported by the hip joints, thus overcoming any difficulties due to differing leg lengths or ineptly applied ankle or leg restraints. In addition, the lap belt can readily be fastened by the end-user when the chair is in its upright position. The user may also use a feet support 8) in Fig. 1 to keep a comfortable posture during the therapy.

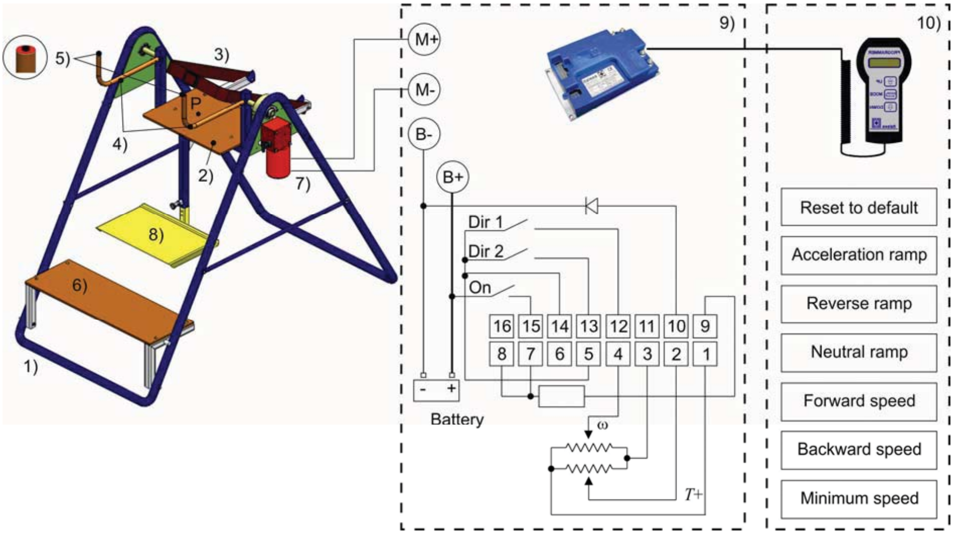


Figure 1. A 3D view of the mechanical design of the novel tilt seat for inversion therapy with actuation and control schemes: 1) Fixed frame; 2) Seat unit; 3) Lap belt; 4) Handlebars; 5) Control buttons; 6) Step; 7) Actuation and transmission system; 8) Feet support; 9) Driver; 10) Teach pendant for programming.

Alternatively, instead of the manual mode, the end-user may upload a pre-loaded program by using the teach-pendant 10), therefore using the so called off-line mode.

The device is actuated and can perform a full rotation of the seat in both directions, through an actuation and transmission system 7), which has been used to transfer the motion from the motor shaft to the main shaft on which the seat tilts. The motor is controlled through its driver 9).

An algorithm has been developed as based on the scheme proposed in (Gonzalez Rodriguez et al, 2011), and it is used to operate the tilt seat in a safe and robust way.

The seat unit can be rocket forwardly and backwardly to perform the inversion. It is worth to note that this is the first device that performs inversion anteriorly and posteriorly with full rotation of 360 deg, therefore, the device can be used either for traction of the spine, but also for stretching and strengthening of the muscles such as the rectus abdominus and obliques.

The end-user may decide which program being executed, but also he/she can act directly on the control buttons to reach any kind of desired orientation to perform static inversion.

Summarizing, substantial differences of this novel design over the existing tilt tables sold on the market can be recognized as: I) a retaining system designed as composed by a lap belt engaging the upper side of the tights; II) a seated configuration during the inversion, which is more comfortable with respect horizontal configuration. Therefore, the hip joints sustain the weight of the torso and the head and lower articulations are free; III) possibility to perform inversion anteriorly and posteriorly, and IV) in a static or intermittent way. Finally, V) the novel mechatronic design leads to a cost reduction and can be considered easy-in-use, as it will be described in the following.

The operation of the system can be summarized as the sequence of actions that should be performed by the end-user: 1) accommodate on the seat unit; 2) fasten seat belt; 3) operate either in manual or off-line modes directly operating on control buttons or on the teach pendant; 4) movement of the seat from upright to inverted configuration; 5) after some time backward rotation to the initial configuration. By analyzing this sequence, crucial phases from the control point of view are represented by the actions 4) and 5) since the end-user should feel comfortable during the inversion. In particular, the end-user defines an orientation of the seat.

In general, a desired rotation can be achieved either in manual and in off-line modes by considering several laws of motion. From the control point of view it is possible to control the rotation speed of the seat (about the so called main shaft) by regulating the angular velocity of the motor shaft. This angular velocity can be directly linked to a reference point velocity of the seat unit. Therefore, it is very important to be able to control the velocity of the seat unit in order to preserve the comfort of the end-user during the inversion. In fact, a generic law of motion can result in a quite uncomfortable motion of the end-user body, neck and head.

2.1. Simulation results

The prototype is equipped by a permanent magnet synchronous motor drive, for which a PI controller may be used because of its simplicity and practicality. In this context a PI speed control scheme has been developed and used as based on the model proposed by (Xu and Gao, 2004). Figure 2 shows a qualitative control scheme for the proposed tilt seat.

In Fig. 2 ω^*_r refers to the reference angular velocity that can be set, which is transformed in a suitable value. The measured rotation φ of the shaft is multiplied by K_T and then differentiated to get the actual angular velocity ω_r of the main shaft. The value of ω^*_r is compared with the actual velocity ω_r giving the error ε. The signal error ε is then sent to a PI controller to obtain the compensated velocity ω_c to drive the tilt seat. Several laws of motion for the angular velocity of the main shaft have been implemented to drive the tilt seat.

In particular, three laws of motion for the angular velocity have been selected to be tested, namely a constant angular velocity that constitute a flat profile I); a ramp profile II), which is a first order profile; and a cubic profile III), which is a third order profile.

These three laws of motion constitute the ω^*_r values, which have been used, according to the control scheme proposed in Fig.2.

Simulations of the proposed mechanical model shown in Fig. 1 have been run in Solidworks environment, by considering a payload of the tilt seat of 100 kg simulating the end-user mass. During the simulation a reference point velocity and acceleration have been measured to test the effects of the inversion on the end-user. Point P has been chosen as reference point, as it is shown in Fig. 1.

Figure 3 shows numerical results of vertical and horizontal components for the velocity of point P, and in Fig. 4 plots are given for the vertical and horizontal components of linear acceleration of point P.

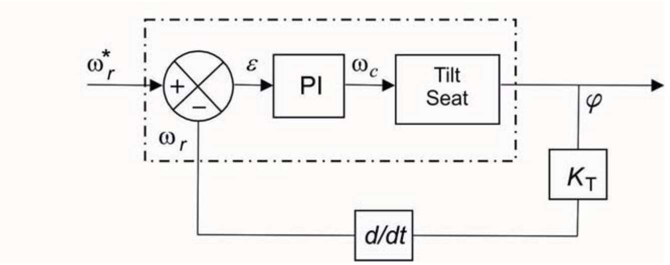
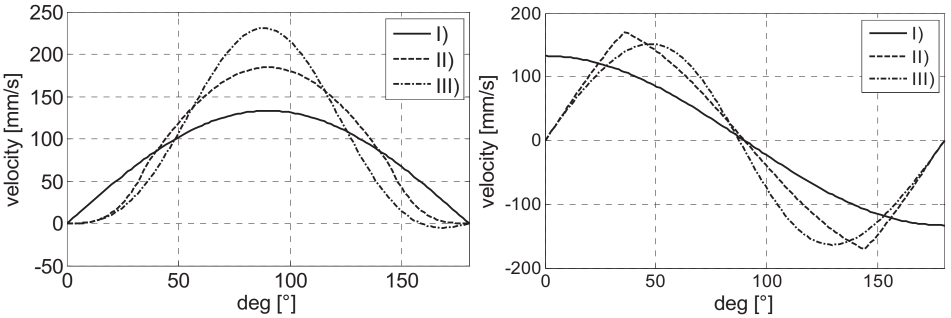
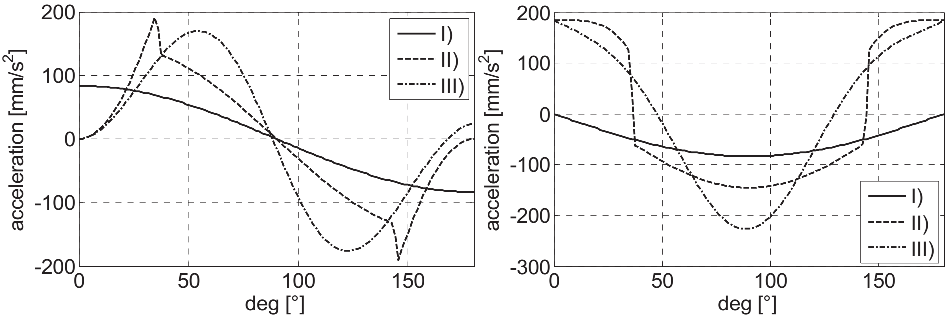


Figure 2. A control scheme for the proposed tilt seat.



a) b)

Figure 3. Numerical results for the simulation of the novel tilt seat, point P linear velocity: a) vertical component; b) horizontal component.



a) b)

Figure 4. Numerical results for the simulation of the novel tilt seat, point P linear acceleration: a) vertical component; b) horizontal component.

By analyzing the plots it can be noted that better results can be obtained with a constant velocity profile I) in Figs. 3 and 4, in terms of point velocity and acceleration, which are smooth with lowest maximum values, if compared with the other two motion laws. This will produce a better comfort for the end-user because it will reflect the body velocity and acceleration during the inversion. Unfortunately, mainly in manual mode, the system will go through several transient profiles and does not practically behave as constant. Therefore, a speed control is required in order to get good performances of the system in terms of smoothness of velocity and acceleration.

Therefore, other two laws of motion have been tested, as reported in Figs. 3 and 4. In particular, either a ramp and a cubic profile give comparable results in terms of smoothness of the velocity and acceleration profiles for point P. Therefore, both of them can be considered for the application.

It is worth noting that in the simulation tests we have considered a reference point P fixed on the seat unit, this is to give a repeatable result that does not depend on anthropometric data of the end-user, and that can be further used during experimental tests.

3. A PROTOTYPE AND EXPERIMENTAL TEST

A prototype of the novel tilt seat has been built for first experimental tests, which are shown in Figure 5. In particular, the test deals with end-user using the manual mode to get a static inversion. It is possible to note from the photo sequence in Fig. 5 that the handlebars are used to support the user, and they can be released when the body is in the inverted position, as it is shown in Fig 5d). The feet support and handlebars can be adjusted according to the anthropometric data of the subject.

The fixed frame 1) in Fig.1 is made of steel in order to have a light and robust structure. It is worth to note that for this first prototype the seat is built in a skeleton form, and the various mechanical parts could be further covered or encased. No such covering or encasement has been shown at this stage since it would merely obscure the operation of the working parts.

The proposed control system has been developed to perform static and intermittent inversion in a safe and robust way, both is manual and off-line modes, as based on previous experiences and experimental test-beds proposed and reported in (Sorli et al, 2005; Figliolini and Rea, 2006).

In particular, in the following, details on the hardware are reported. It is worth to note that at this stage the control panel visible in Figure 5 is left open to appreciate the electrical and electronic boards/units inside. The driver 9) in Figure 1 allows the control of velocity, acceleration and torque thanks to a microprocessor with 4 quadrants for PM DC Motors of type Italsea, 7CH4Q45(N).

The actuation system is composed by a DC gear motor with permanent magnet of type AMER, MR07. The transmission system is a gearbox, it is realized by a steel worm and worm gear rolled or rectified with bronze gear with a reduction ratio of 30/1. Voltage is 24V, the gearbox release system is available, with a power up to 400W and an electromagnetic brake.

The teach pendant 10) in Fig. 1 with Italsea programmer model 7PROGLCD allows to set the following parameters: forward velocity, backward velocity, acceleration ramp, reverse ramp, brake delay.

It is worth noting that at this stage simulations and a prototype were tested from the mechatronics and mechanical point of view, without direct testing on volunteers. Further developments of the proposed mechatronic device are directed towards clinical experimentation dealing with suitable protocols and improvements of the developed prototype.

An Italian Patent has been recently submitted as based on the proposed invention (Rea et al., 2012).

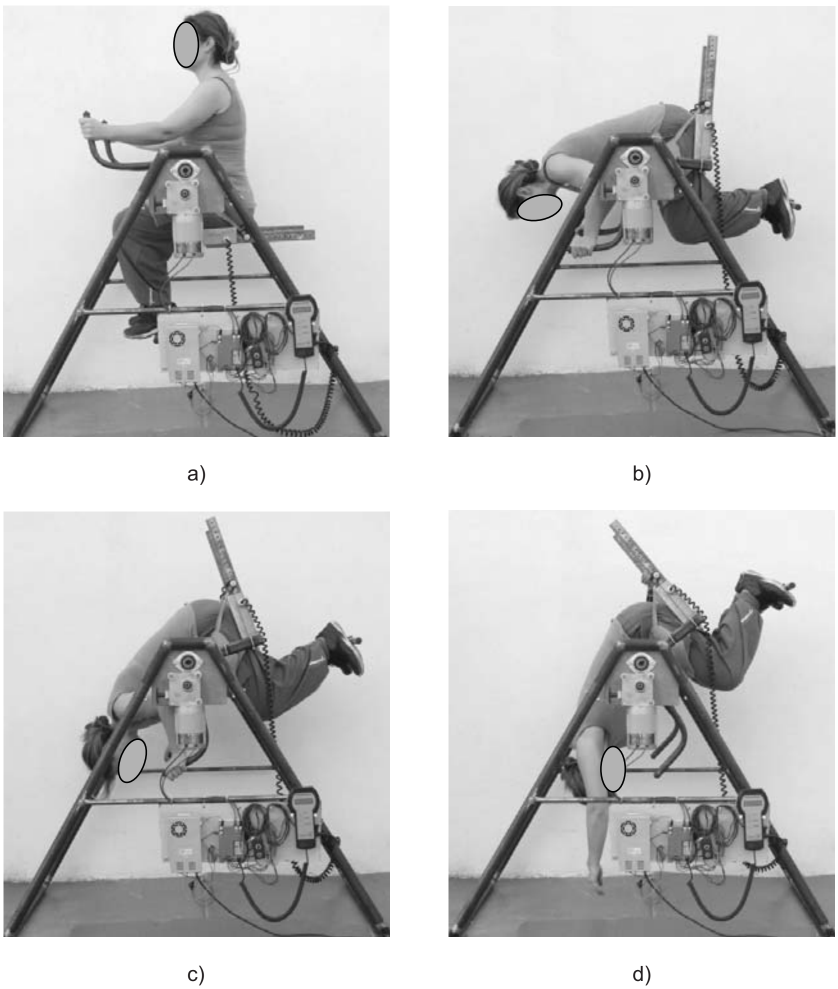


Figure 5. A photo sequence of an experimental test of the novel tilt seat for inversion therapy.

4. CONCLUSIONS

In this paper a novel mechatronic design for a tilt seat is proposed and a prototype has been built for first experimental tests. Main novelties from the existing devices for inversion therapy can be recognized in the use of a seat that allows more comfortable upright and inverted positions. Moreover, having a thigh engaging system wide enough to engage a substantial area of the surface of the thighs of a user it is possible to maintain them substantially parallel to seat, whereby when the seating unit is in the traction position a major component of the weight of the head and torso is suspended through the hip joints and do not use ankle joints. Furthermore, the device can be used either for traction and restoration of the physiological curve of the spine, but also for and toning of lumbar, back and abdominal muscles because it can perform inversion anteriorly and posteriorly. The mechanical design is proposed together with actuation and control scheme. Simulations were run to test the engineering feasibility of the proposed device with the aim to get comfortable operation of the system. Numerical simulation and first experimental results with a built prototype are also shown. Future work on the control design will concern with the development of more sophisticated control strategies according to the results obtained by clinical tests in order to improve the efficiency and robustness of the tilt seat during the therapy and the comfort of end-user.

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