DEVELOPMENT OF A MECHATRONIC SYSTEM 'GAITSIM' FOR BIOMECHANICAL REHABILITATION OF PATIENTS-PARAPLEGICS

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A structural solution of a mechantronic system used for human foot receptor activation is presented. A biomechanical approach is adopted to synthesize the system. Experimentally found data for the dynamic characteristics of a normal walk are used. The use of the system for the rehabilitation of patients-paraplegics is verified by studying the effect of foot receptor signals on locomotion. The system provides a receptor activation that simulates walk of a patient with serious paralysis of the lower limbs, i.e. a patient-paraplegic.

The report introduces: a basic scheme of the system, a technical solution of the specific modules and choice of a set of elements needed for foot loading considering the dynamic characteristics of normal human walk. Different loading regimes are provided. Parameters subjected to regulation are the simulated walk speed and the maximal value of the foot loading.

Key words: *mechantronic system, foot receptor activation, functional rehabilitation*

1. Introduction

Based on clinical investigations performed during the recent years, it stands clear that durable training of patients-paraplegics who undergo external support and passive limb movement on a thread-band implies rehabilitation of their capability to perform primitive walk [1–3]. Besides, the value of pressure on the support area (foot) becomes a critical factor for the initiation of locomotion-like movement (pacing).

Normally, walk is a process where the left foot and the right one undergo rhythmical and shock loading which is applied in a specific succession. Thus, the activation of the foot receptors is automatically maintained. The receptor signals form a sufficient data flow that serves as a biological feedback. The latter maintains locomotion generation and regulation. In case of spinal cord break as a result of a trauma or disease, a serious functional upset occurs. Data flow to the high sections of the nervous system is cut, but the information links with the spinal cord from below and to the break spot are kept. Neuro-physiological studies prove that nerve conductivity is lost in a month after the spinal cord break. The

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performance of the support-locomotion system is blocked. The patient looses his capability of independent movement and immobilization yields atrophy of his skeleton-muscle system (muscles, bones, joints). Considering this a set up, the probability of physical, psychical and social rehabilitation of such a contingent of patients is minimal.

2. Task, problems and approach employed for the development of a specialized mechatronic system 'GAITSIM'

The basic task of the study is as follows: considering patient's serious trauma, find a method for the simulation of patient's walk close to the normal one; maintaining data flow from the foot receptors, stimulate the locomotion capabilities of the spinal cord and the functioning of patient's support-locomotion system. To fulfill the task, we develop a specialized mechatronic system to solve the following problems:

1. Attaining maximal comfort of the system individual use by patients-paraplegics during the earliest possible post-traumatic period;
2. Limitation of the atrophy of patient's support-locomotion system, yet without the performance of locomotion-like movement of the lower limbs;
3. Initiation of data flow from the foot receptors to stimulate the rehabilitation of the locomotion capabilities of the spinal cord;
4. Maintenance of the activation of the nerve ends, located on the feet and corresponding to the internal organs, to stimulate and maintain organ functioning, regardless of patient's immobilization.

Applying a biomechanical approach for the system development, we look for a solution of the system mechanics, actuation and control that would provide patient's feet loading similar to that of a normal walk. We use as a standard the graph of the vertical support reaction in the single-support stage of walk.

3. Dynamics of human foot loading

Biomechanical studies show that one of the most sensitive and informative parameter characterizing locomotion and reflecting the state of the human supportůlocomotion system is the vertical component of the support reaction occurring during walk [4–6].

Fig. 1 shows the graph of the vertical support reaction of a foot under normal walk.

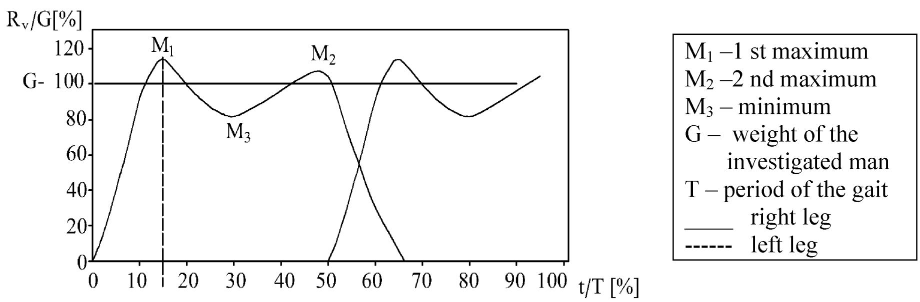


Fig.1: A graph of the vertical support reaction of a foot under normal walk

Maximum 1 corresponds to the holding period of the support stage – heel support. Maximum 2 corresponds to the push period of the support stage – toe support. The local minimum of the curve corresponds to shift of the opposite leg, i.e. to minimal loading of the whole supporting foot. The horizontal line of Fig. 1 corresponds to the weight of the investigated man (weight level). All extremums are located significantly above or below the specified level. This illustrates the walk dynamic character and proves that muscle, gravitation and inertia forces effectively operate during walk. The graph allows accounting for the durability of the support stage periods.

We use the graph as a standard when planning patient's foot loading in accordance with the three periods of the support stage. The curve interpolation is performed at three points (extremums). However, in favor of the rehabilitation of patients-paraplegics who have been immobilized for a long period of time and considering the occurring atrophy of the skeleton-muscle system, one should reduce the value of the maximal load.

4. Technical solution of the mechatronic system 'GAITSIM' for the simulation of human walk dynamics

4.1. System configuration

The general scheme of the specialized mechatronic system is shown in Fig. 2, Fig. 3. The system consists of: 1 – module for foot dynamic loading (2 pieces); 2 – module-controller (2 pieces); 3 – computer for system control (compatible with IBM PC).

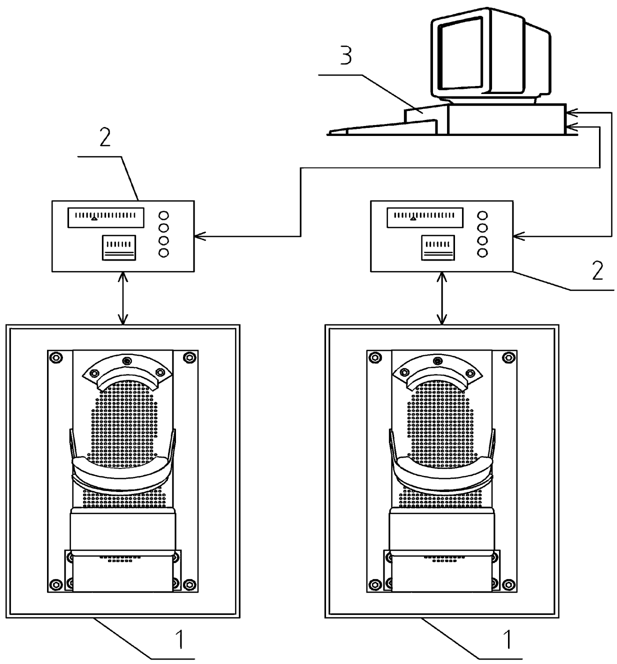


Fig.2: General scheme of the mechatronic system for the simulation of human walk dynamics: 1 – module for foot dynamic loading, 2 – module-controller, 3 – computer for system control

The system comprises two identical modules 1 for the left and right foot, respectively. Following a given program specified by the computer, the devices provide foot loading in compliance with the walk rhythm. Hence, walk with a specified speed is simulated.

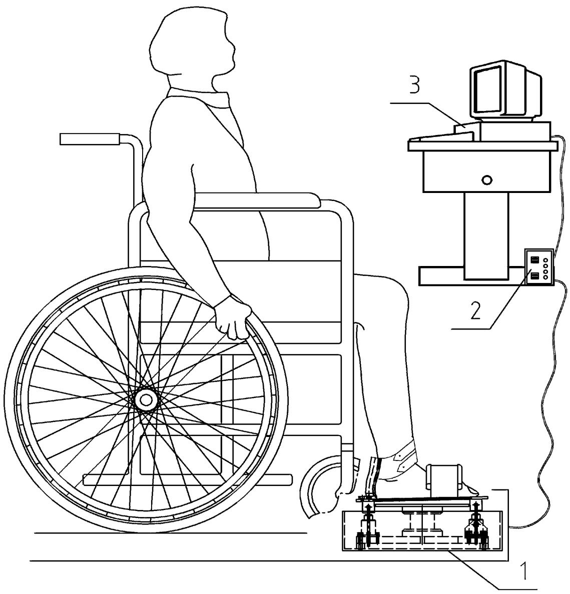


Fig.3: General view of the 'GAITSIM' systems assisting a patient

Accounting for the walk temporary characteristic, periods of single and double support are realized together with the corresponding loading of each foot.

4.2. Structural solution of the module for foot dynamic loading

The structure of the module for foot dynamical loading is shown in Fig. 4, Fig. 5, Fig. 6 and Fig. 7.

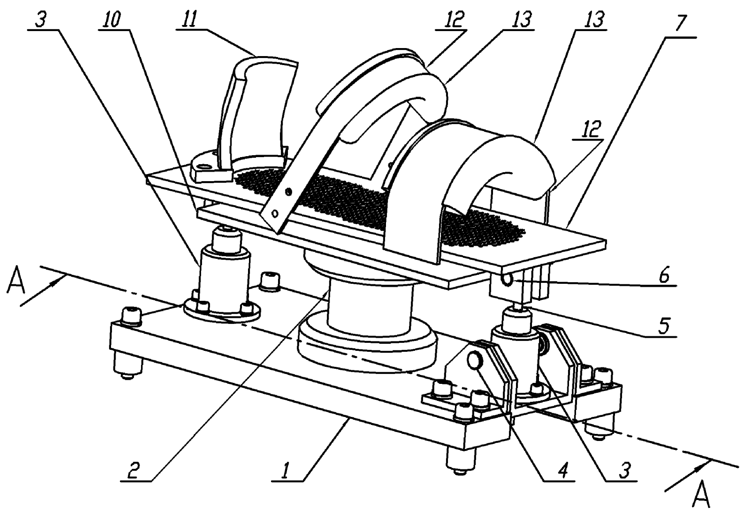


Fig.4: Axonometric view of the module for foot dynamic loading : 1 – immovable plate; 2 – power transducer; 3 – linear motor; 4 – axis; 5 – axis; 6 – hinge; 7 – movable plate; 8 – pin; 9 – ring; 10 – plate; 11 – foot stop; 12 – elastic belt; 13 – pressing cushion

The module structure is described in what follows. A lower immovable plate 1 is used as a structure element and a power transducer 2 is fixed to its centre. Two linear motors 3 are mounted at both ends of the immovable plate 1. One of the motors is firmly fixed while the other one hangs on a hinge on axis 4. A movable plate 7 with apertures is attached to axes 5 of the linear motors by means of hinges 6. Pins 8 with stop rings 9 are inserted in the apertures of movable plate 7. The lower ends of pins 8 touch plate 10. Plate 10 is mounted on the power transducer 2 which in its turn is fixed to the lower side of movable plate 7. Foot stops 11 and elastic belts 12 with attached pressing cushions 13 are fixed to movable plate 7.

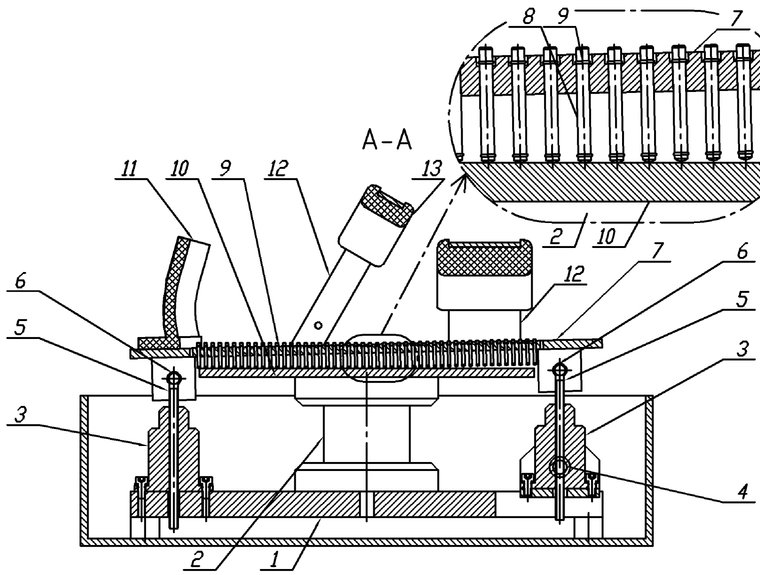


Fig.5: Cross section A–A of the module shown in Fig. 4

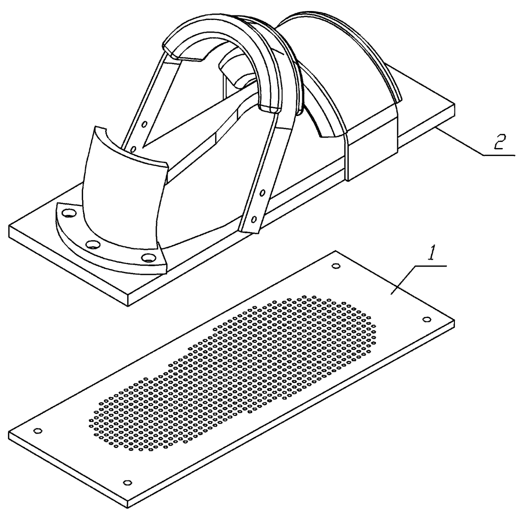


Fig.6: System for fixing patient's foot : 1 – upper immovable plate (grid), 2 – movable pins

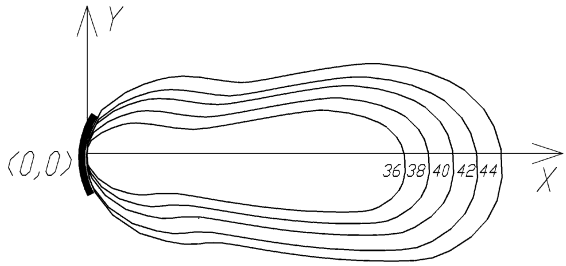


Fig.7: Dimension versions of the foot fixing system

Movable plate 7 (Fig. 4, Fig. 5) equipped with pins and a system for foot fixing is compounded of two parts, as shown in Fig. 6. Position 1 in Fig. 6 shows the movable plate with the pin matrix. The matrix (grid) is shaped as a human foot. Its dimensions correspond to the maximal dimensions of the human foot.

The foot fixing system 2 is mounted to plate 1 (Fig. 6) and it specifies patient's foot individual size. It is to be manufactured, considering a sufficient number of human foot sizes as shown in Fig. 7. Thus, the basic mechanical system would become universal and an individual foot fixing system could be selected for each patient.

4.3. Functional realization of foot loading in compliance with the walk rhythm

Software sets up walk with a specific period T, while at the same time walk is simulated by the mechanical system – Fig. 8. The two basic stages of walk, i.e. walk fly stage (Fig. 8a) and walk support stage for each leg (Fig. 8b, c, d), are simulated during loading. Load transfer from leg to leg is performed. This means that load transfer from a single support of the right leg to a single support of the left leg is performed passing through the corresponding stages of double support. Foot load for a single support is applied, following the graph of the vertical support reaction plotted for the three stages of the support phase of normal walk (Fig. 1). Fig.8 shows load application for :

– fly stage :
  a) – loading 0 N;
– support stage :
  b) – holding period (heel support),
  c) – period of support of the entire foot,
  d) – push period (toe support).

Loading during heel support (b) is calculated considering maximum 1 of the graph of the vertical support reaction of normal walk (Fig. 1). Loading during the stage of support of the entire foot (c) is calculated accounting for the local minimum of the same graph. Loading during the stage of toe support (d) corresponds to graph maximum 2. Thus, the graph of the vertical support reaction is approximated at three points. The module described performs loading of one of the legs. A similar module is used to load the other leg.

4.4. Technical characteristics of linear step motors

Linear step motors manufactured by the company Haydon Switch&Instruments Inc., USA are used in the system. Motors are of the type E87H4 (2)-5, bipolar, 5 V, with maximal linear stroke of 12.7 mm. Motors technical specifications are given in Fig. 9 and Fig. 10.

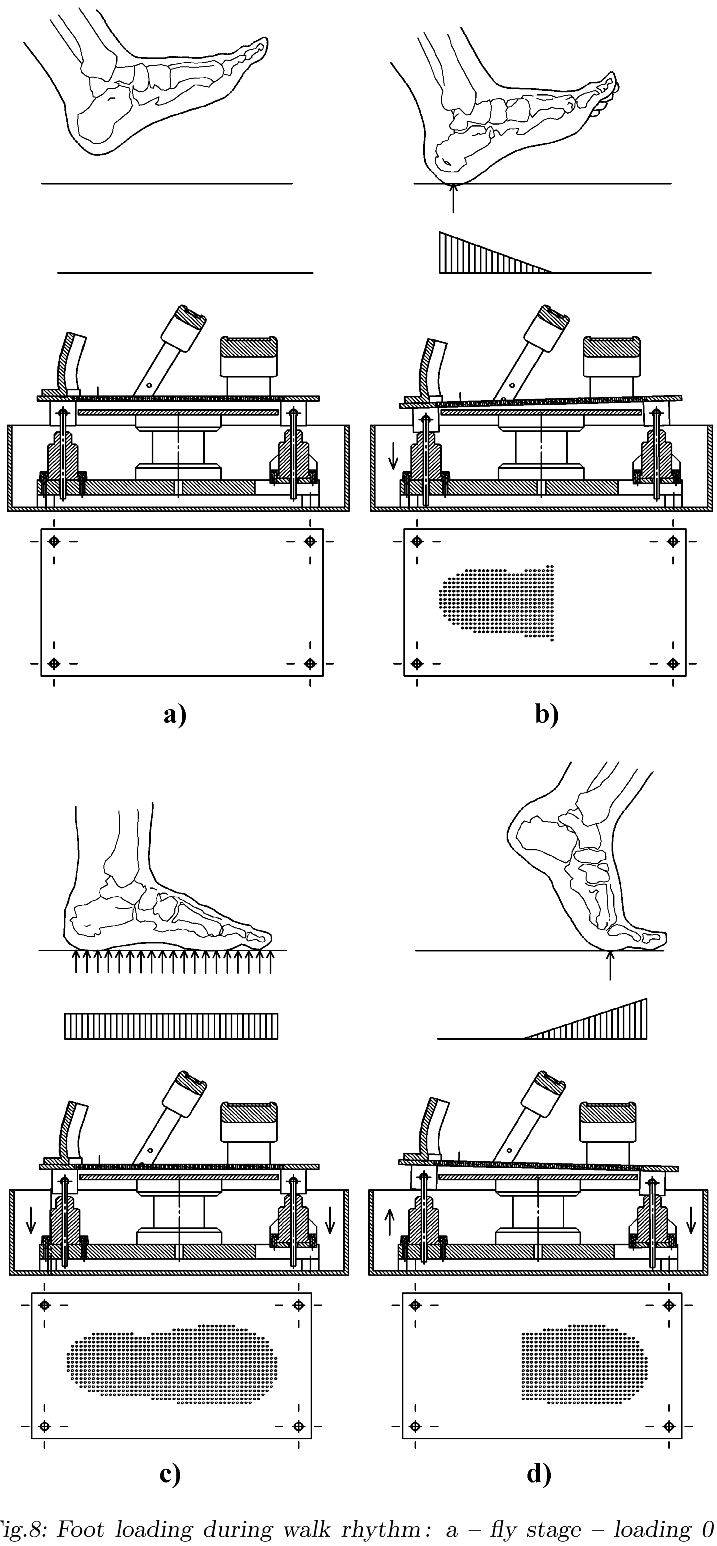
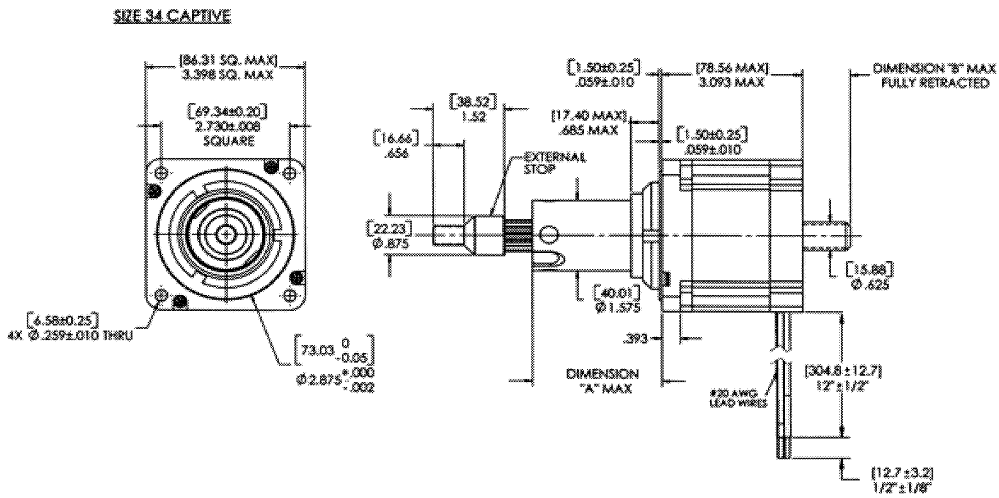


Fig.8: Foot loading during walk rhythm: a – fly stage – loading 0 N; support stage: b – holding period (heel support), c – period of support of the entire foot, d – push period (toe support)

Size 34: 87 mm (3.4”) Hybrid Linear Actuator (1.8 Step Angle)					
Part number | Captive	E87H4(X)-V			E87H6(X)-V	
Wiring	Bipolar			Unipolar*	
Operating voltage	2.5 VDC	5 VDC	12 VDC	5 VDC	12 VDC
Current/phase	6.24 Amps	3.12 Amps	1.3 Amps	3.12 Amps	1.3 Amps
Resistance/phase	0.40 Ω	1.6 Ω	9.23 Ω	1.6 Ω	9.23 Ω
Inductance/phase	2.2 mH	8.8 mH	51 mH	4.4 mH	25.5 mH
Power consumption	31.2 W				
Rotor inertia	1760 gcm^2				
Temperature rise	167 °F (75 °C)				
Weight	5.1 lbs. (2.3 kg)				
Insulation resistance	20 MΩ				

Fig.9: Technical specifications of a motor type E87H4 (2)-5



ST	DIM	DI
0.5	1.225	0
1.0	1.725	0
1.5	2.225	0.75
2.0	2.725	1.25
2.5	3.225	1.75

Fig.10: Technical specifications of a motor type E87H4 (2)-5 (stroke 12.7 mm)

Motor dynamic characteristics are given in Fig. 11. Version 2 with 0.0635 mm/step stroke is selected out of the 5 possible versions that provide stroke discretization in mm/step.

Control is performed with a speed of 500–900 step/s. Then, for a speed of 500 step/s, linear speed of 31.75 mm/s is attained. The pin maximal stroke – 5 mm is attained for 0.157 s corresponding to the realization of maximum 1 of the graph of the vertical support reaction (Fig. 1). Considering this speed value and following Fig. 11, 600 N per motor and 1200 N per a device are realized, respectively. Increasing the number of steps per second, i.e. the speed, loading can be regulated as shown in Fig. 11. Driver ‘L/R Driver 40105’ manufactured by the same company is used for motor control.

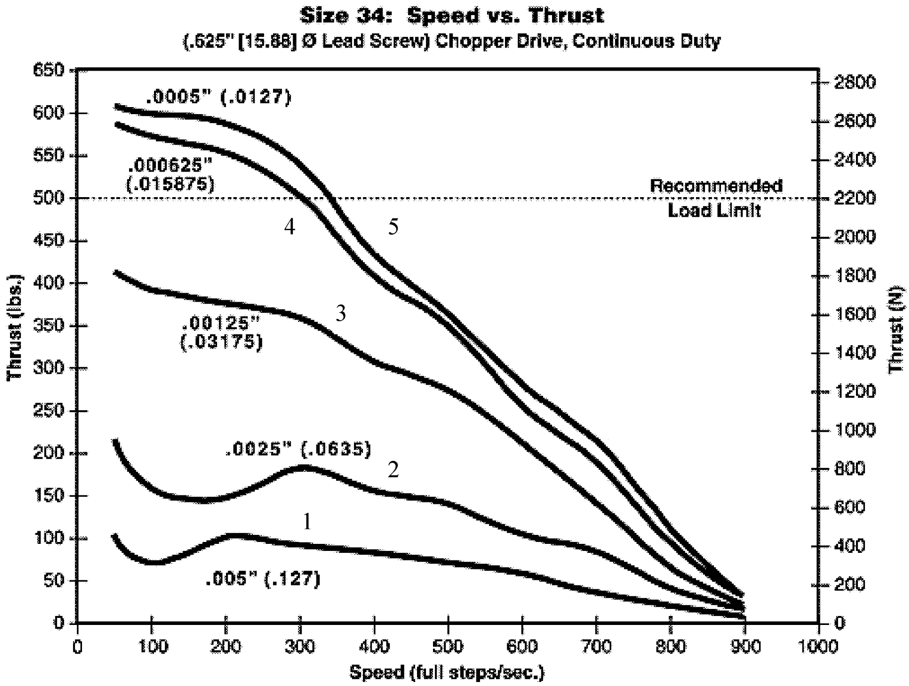


Fig.11: Dynamic characteristics of a motor type E87H4 (2)-5, (variant 2); dimensions in brackets ( ) are in millimeters

5. Performance and application of the bio-mechabtronic system 'GAITSIM'

The 'GAITSIM' biomechatronic system is used as shown in Fig. 2, Fig. 3, and Fig. 4. The human foot is placed on the movable plate 7, where the foot stop 11 specifies heel position, and foot is pressed to the plate by means of elastic belts 12 and cushions 13. Applying a single or combined displacement of the linear motor axes 5, the movable plate 7 executes movement similar to foot movement during walk, partially or entirely pressing all pins 8 to the immovable plate 10. Owing to their larger length, pins protrude from the plate upper side and exercise pressure on the foot surface, and pressure is equal to that applied on the power transducer 2. The control of linear motors 3 is performed by means of software and through an interface 15 and PC 16. The following parameters are controlled – foot size, foot pressure controlled by the power transducer and rhythm of the simulated walk.

6. Areas of application of the biomechatronic system 'GAITSIM'

The mechatronic system for loading the human foot in compliance with the walking rhythm is appropriate for application in two areas:

- fundamental studies of control of the spinal cord locomotion activity in the absence of links with the high sectors of the nervous system as a result of spinal cord trauma or disease;
- functional rehabilitation of:
  1. Patients-paraplegics;
  2. Patients with serious orthopedic traumas, immobilized for a long period of time;
  3. Prophylactic functional stimulation of people who work sitting all day.

7. Final remarks

The biomechatronic system 'GAITSIM' developed is characterized by computer control, original design of the mechanical modules, specialized software and methods for functional rehabilitation of patients suffering from long-term immobilization. It can also be used to prevent the development of orthopedic and neurological diseases.

Acknowledgement

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References

[1] Diez V., Colombo G., Lensen L., Baumgartner L.: Locomotor capacity of spinal cord in paraplegic patients, Ann. Neurol. 37, 1995, 574–582
[2] Diez V., Wirz M., Curt A. and Colombo G.: Locomotor pattern in paraplegic patients: training effcts and recovery of spinal cord function, Spinal Cord. 36, 1998, 380–390
[3] Shik M.L.: Recognizing propriospinsl and reticolospinsl systems of initiation of stepping and stending, Motor Control 1, 1997, 310–313
[4] Winter D.A.: Biomechanics and motor control of human movement, John & Sons, Inc., 1990, pp. 273
[5] Willams & Lissner's, 3/e: Biomechanics of human motion, W. B. Saunders company, 1992, pp. 326
[6] Yanson H.A.: Biomechanics of Human Lowver extremity (in Russian), Zinatne, Riga, 1975, pp. 324

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