Pneumatic Muscle Actuated Isokinetic Equipment for the Rehabilitation of Patients with Disabilities of the Bearing Joints

Tudor Deaconescu, Andrea Deaconescu

***Abstract*— Applying continuous passive rehabilitation movements as part of the recovery programme of patients with post-traumatic disabilities of the bearing joints of the inferior limbs requires the development of new high performance equipment. The paper discusses a study of the kinematics and performance of such a new isokinetic rehabilitation system actuated by pneumatic muscles. The utilized energy source is compressed air ensuring complete absorption of the end of stroke shocks, thus minimizing user discomfort.**

***Index Terms*— isokinetic equipment, pneumatic muscle**

I. Introduction

The paper presents a variant of equipment designed for the recovery of patients with posttraumatic dysfunctions of the bearing joints of the lower limbs (knee and hip), by application of continuous passive rehabilitating motions. The novelty of this equipment consists in its actuation, namely by pneumatic muscles.

Rehabilitation medicine claims as its specific objectives maintenance and recovery of the functions of the human body, prevention of its dysfunctions, using in this respect kinetic and orthotic techniques, as well as various supporting and adaptive accessories.

At present several methods are used in order to alleviate the dysfunctions of the bearing joints (hip, knee), like passive joint mobilization exercises for avoiding contractures of the paretic limbs, muscle force exercises for correcting the contractures of the spastic muscles of the limbs, utilization of adaptive equipment for promoting the function (limb prostheses, ortheses, walking supports).

The main form of recovery of the diminished functions is kinetic-therapy including techniques involving motion, as well as various forms of relaxation and immobilisation (postural techniques) [1], [2]. Although necessary and beneficial in many situations, the posttraumatic resting of the bearing joints need to be limited in time, given its known negative effects on the neuro-muscular, osteo-articular, cardio-vascular, respiratory and other structures and functions. Recent studies have proved that although bed rest alleviates pain, its duration needs to be short, not exceeding 2-3 days. Prolongation of bed rest is accompanied by negative effects also at other levels: psychological (perception of a severe disability), economic (absence from working and social life), loss of muscular condition (atrophy), diminished cardio-pulmonary function, acute complications (thrombo-embolisms, loss of mineral bone mass, hypercalcemia and hypercalciuria).

International studies have revealed that the deployment of equipments capable of performing continuous passive motions for rehabilitation purposes has contributed to diminishing rehabilitation costs by about 50%.

For these reasons, a relatively short resting period needs to be followed by isokinetic motions, subsequently continuous passive, then assisted active and eventually unassisted active.

In the case of the lower limb and its bearing joints passive kinetic-therapy will be able to counterbalance the tendency to external rotation, flexia and adduction of the hip, knee flexia and plantar flexia of the foot, insisting on passive abduction motions, on internal hip extension and rotation, on knee extension and foot dorsiflexia, in order to prevent the retraction of the Achilles tendon.

The necessity of conceiving modern complex equipment required for the rehabilitation of patients suffering fro posttraumatic dysfunctions of the lower limbs results from the high incidence of such disabled persons. A study carried out by the Rehabilitation Clinic of the INRMF of Bucharest ha revealed that in the period from 2002 to 2005, of 4323 admitted patients a number of 835, representing 19.32% were suffering from posttraumatic dysfunctions of the bearing joints. Other 877 patients, representing 19.32% were suffering from degenerative rheumatisms, therefore also qualifying as potential beneficiaries of kinetic-therapy.

Research carried out on a sample population of 150 patients having benefited from kinetic-therapy has yielded the following conclusions:

a. improvement of the pain score by 30.02%;
b. improvement of physical dysfunctions by 14.99%;
c. improvement of disabilities by 24.22%;
d. improvement (reduction) of medication consumption by 21.82 %;
e. improvement of the general average score for the entire lot by 24.12%, the highest values corresponding to the group

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Prof. Dr. Eng. Tudor Deaconescu is with the Transilvania University of Brasov, Vice-Dean of the Faculty of Technological Engineering, Department of Economic Engineering and Production Systems, Bd. Eroilor 29, Romania, RO-500036 (phone: 0040-268-477113; fax: 0040-268-477113; e-mail: tdeacon@ unitbv.ro).

Associate Prof. Dr. Eng. Andrea Deaconescu is with the Transilvania University of Brasov, the Faculty of Technological Engineering, Department of Economic Engineering and Production Systems, Bd. Eroilor 29, Romania, RO-500036 (phone: 0040-268-477113; fax: 0040-268-477113; e-mail: deacon@ unitbv.ro).

suffering from hip fracture (27.74%), followed by knee fractures (22.85%) and ankle fractures (19.76%).

Within the studied sample the distribution of posttraumatic dysfunctions was: 43.33% of the cases with hip fractures, followed by knee fractures (30% of the cases) and ankle fractures (26.67% of the cases).

These studies argue clearly for the necessity of introducing kinetic-therapy as a compulsory means of posttraumatic treatment of the bearing joints, the continuous passive motion representing an optimum instrument in the therapeutic toolkit of rehabilitation professionals.

Continuous Passive Motion (CPM) is a post-operatory recovery treatment method applied in the case of lower limb bearing joint surgery. After such surgery the tissue surrounding the wound becomes rigid, thus contributing to a diminished mobility of the respective joint. In certain cases the duration of natural recovery of mobility may be as long as several months.

The utilization of the principle of continuous passive motion entails the mechanized actuation of the concerned joint without the self-straining of patient muscles. This is possible by using specially conceived equipment, capable of applying the optimum motions to the joints, necessary for rehabilitation.

Completed research has proved that the utilization of such equipments would significantly reduce the period of recovery, the patients resorting to a smaller quantity of pain medication. Hence the total costs of recovery are significantly diminished.

II. Isokinetic Equipment

Isokinetic equipment developed to date can be divided into two categories: pluri-articular (multi-joint) devices allowing by means of accessories the testing and rehabilitation of most major joints, and mono-articular (single-joint) devices aimed at a single specific joint. Worldwide such systems have been developed specially designed for knee or ankle recovery, as the one illustrated in Fig. 1.

All isokinetic equipment are endowed with computerized control allowing the real-time study of muscle functionality, as well as the plotting of a series of curves (diagrams) for the study of muscle contraction along the entire path of the motion. Such control represents also an important means of feedback for the patient, as well as the basis for functional assessment to be carried out by the physician during the isokinetic test.

Fig. 1 Fastening of the leg in an isokinetic rehabilitation equipment (Fisiotek)

The advantage of such equipment is that their utilization not restricted to specialised rehabilitation centres, as they lend themselves to home deployment as well.

All isokinetic equipment required for continuous passive motion currently available on the market place are driven by electric motors with a rigid linkage structure. The prices of such equipment are high, in the range of thousands of Euros, often exceeding the financial possibilities of the potential users.

The carried out research yielded the idea of conceiving pneumatic muscle actuated isokinetic equipment for the continuous passive motion of bearing joints, at a final cost below the current offers available on the market place.

III. Pneumatic Muscle Based Actuations Systems

One of the most attractive aspects of pneumatic actuation is the low weight of the utilized components, and implicitly their favourable response to commands. Favourable response to commands, known as compliance is due to air compressibility, and hence can be influenced by controlling/adjusting the command pressure. Compliance is an important property concerning the man - machine relationship, as well as the completion of operations of high sensitivity, like the handling of fragile objects. Compliance ensures a soft contact as well as the safety of the human individual interacting with the working equipment.

Thus the development of light, pneumatic muscle actuated rehabilitation equipment represent a solution worth exploring, given its potential of yielding high performance kinetic-therapeutic systems [3], [4], [5].

The pneumatic muscle is system based on a contracting membrane, which, under the action of compressed air increases its diameter and decreases its length. Thus the pneumatic muscle carries out a certain stroke, depending on the level of the feed pressure. Fig. 2 presents the working principle of a pneumatic muscle.

A pneumatic muscle includes an interior tube that can have various lengths and is made from an elastic material, typically neoprene. This tube is wrapped in a multilayer tissue made from nylon, strengthening and protecting it from the influences of the working environment. The enveloping angle of the tissue, denoted by α, is of 25.4º in the relaxed state of the muscle and of 54.7º at maximum contraction. The force developed by pneumatic muscle is given by (1) [6].

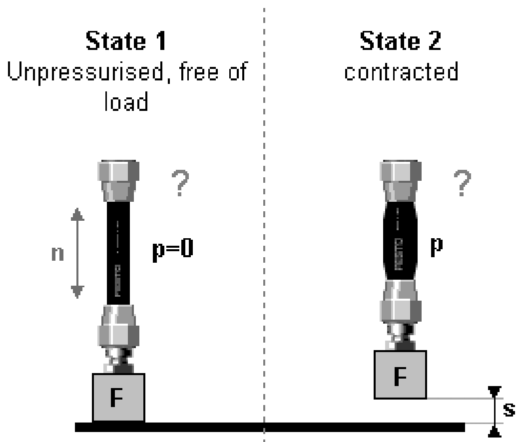

Fig. 2 Working principle of a pneumatic muscle

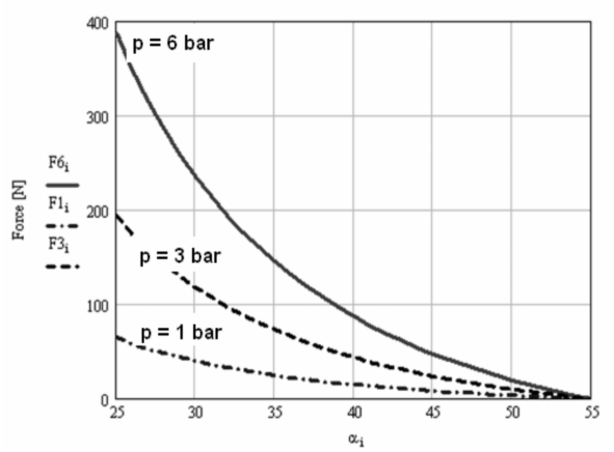

Fig. 3. Force versus enveloping angle and working pressure

$$F = p \cdot \frac{\pi}{4} \cdot d^2 \cdot \left[\frac{3 \cdot \cos^2 \alpha - 1}{1 - \cos^2 \alpha} \right] \tag{1}$$

where p is the working pressure and d the interior diameter of the pneumatic muscle.

The behaviour of the pneumatic muscle is similar to that of a spring, meaning that upon completion of the maximum stroke the developed force is equal to zero. Equation (1) allows plotting of the graph featuring the force developed by a pneumatic muscle versus the enveloping angle and feed pressure (Fig. 3) [7].

IV. Proposed Isokinetic Equipment

Lately the Transilvania University of Brasov has been involved in research related to the utilization of pneumatic muscles. Thus variants of pneumatic muscle actuated non-anthropomorphic gripper system have been developed, as well as a number of normalizable linear motion and rotation modules with the same drive. Further on a variant of rehabilitation equipment is presented, capable of achieving continuous passive motion, by means of a pneumatic muscle actuated system. Fig. 4 illustrates the diagram of principle of the equipment.

The patient undergoing rehabilitation is lying on a bed, as shown in Fig. 5. The equipment allows recovery exercises of the hip and knee joints, the lower limb being immobilized in the device.

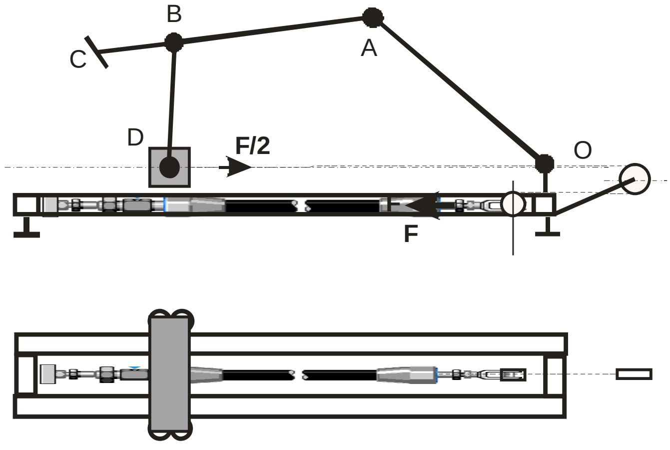

Fig. 4 Operating principle of the isokinetic equipment

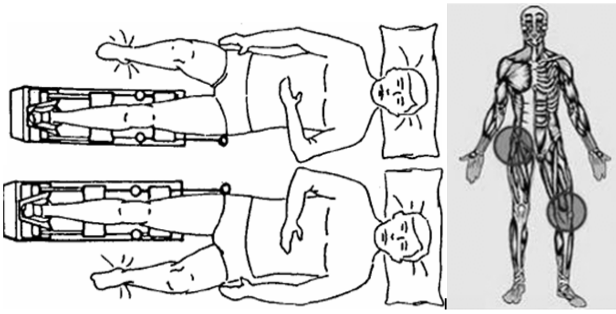

Fig. 5 Patient position during recovery treatment with the isokinetic equipment

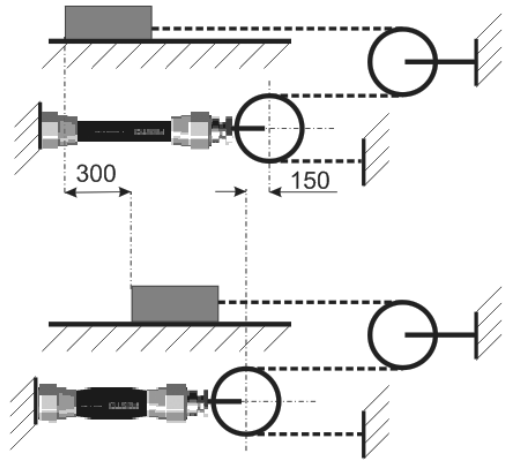

Fig. 6 Actuation of the isokinetic equipment

The equipment can be utilized similarly for both the right and the left leg, due to its axially-symmetrical construction. The continuous passive motion is generated by a pneumatic muscle moving a sliding block, as follows from Fig. 6 [8], [9].

As shown in the figure, the required stroke of the sliding block is of 300 mm. The pneumatic muscle used in the construction of the equipment is of 20 mm interior diameter and initial length of 750 mm, the maximum possible stroke of the free end of the muscle being of approximately 20% of its length in relaxed state (that is 150 mm). A mobile pulley was placed between the muscle and the sliding block in order to amplify the sliding block stroke to the required value.

In order to achieve the desired rehabilitation motions, the sliding block is linked to a mechanism with a flexible bar mechanism, its configuration being presented in Fig. 7.

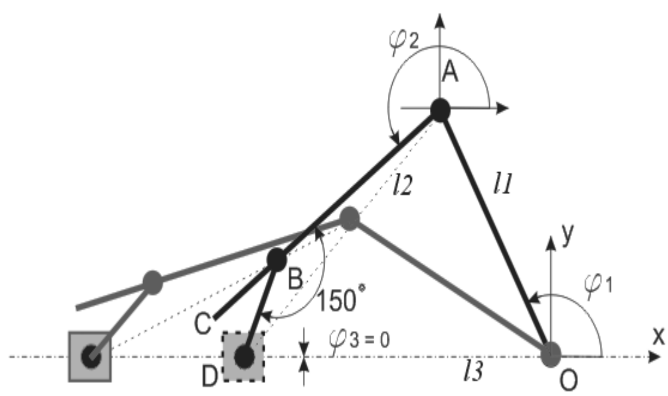

Fig. 7 Kinematic diagram of the flexible bar mechanism

For the mechanism shown in Fig. 7 the variation limits of the rotation angles of the hip joint φ1 and the knee joint, φ2, respectively, can be calculated, and also the evolution of these angles can be represented for the entire duration of the sliding block double stroke. The input value considered for this purpose is the sliding block travel over a 300 mm distance, the unknowns being the two angles φ1 and φ2. Also known are the lengths of the bars, as follows: l1 = 450 mm; l3 = 600…900 mm. In triangle ABD the length of segment l2 = AD can be calculated as being of 552 mm.

The following equations can be written in triangle OAD:

$$l1 \cdot \cos\varphi 1 \quad + \quad l2 \cdot \cos\varphi 2 \quad + \quad l3 \cdot \cos\varphi 3 \quad = \quad 0 \qquad (2)$$

$$l1 \cdot \sin\varphi 1 \quad + \quad l2 \cdot \sin\varphi 2 \quad + \quad l3 \cdot \sin\varphi 3 \quad = \quad 0 \qquad (3)$$

Upon processing these equations and imposing the condition φ3 = 0, the magnitude of angle φ2 can be computed:

$$\varphi 2 \quad = \quad \pm \arccos\left(\frac{l1^2 \;-\; l2^2 \;-\; l3^2}{2 \cdot l2 \cdot l3} \right) \qquad (4)$$

followed by the computation of angle φ1:

$$\varphi 1 \quad = \quad -\arcsin\left(\frac{l2}{l1} \cdot \sin\varphi 2 \right) \qquad (5)$$

Fig. 8 and 9 show the variations of these two angles with the displacement of the sliding block between its extreme positions (-900…-600 mm):

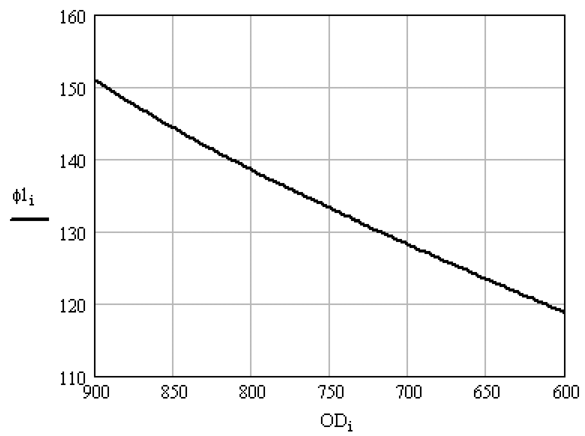

Fig. 8 φ1 = f(l3)

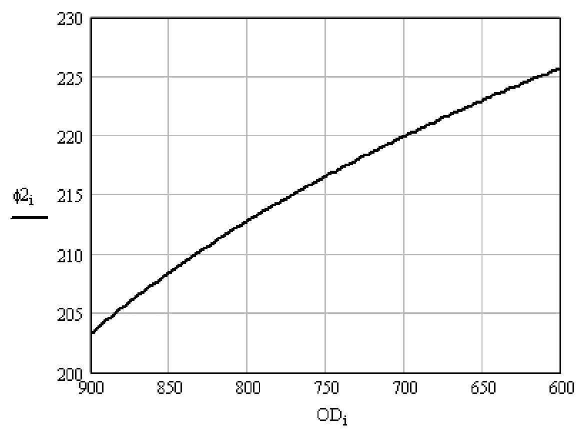

Fig. 9 φ2 = f(l3)

As follows from the graphs, the variation limits of the two angles are the following:

- For the hip joint: φ1 = 118,7 º…..151,037 º;
- For the knee joint: φ2 = 203,347 º…..225,754 º.

The graphs below (Fig. 10) show the time related evolution of the sliding block speed and of the two angles, considering the stroke length of 300 mm being achieved in 2 seconds.

The study of the time related evolution of the actuating pneumatic muscle during its deflation follows from the diagrams presented in Fig. 11. The variations of speed and acceleration versus time can be observed here, as well as of the position of the free end of the muscle.

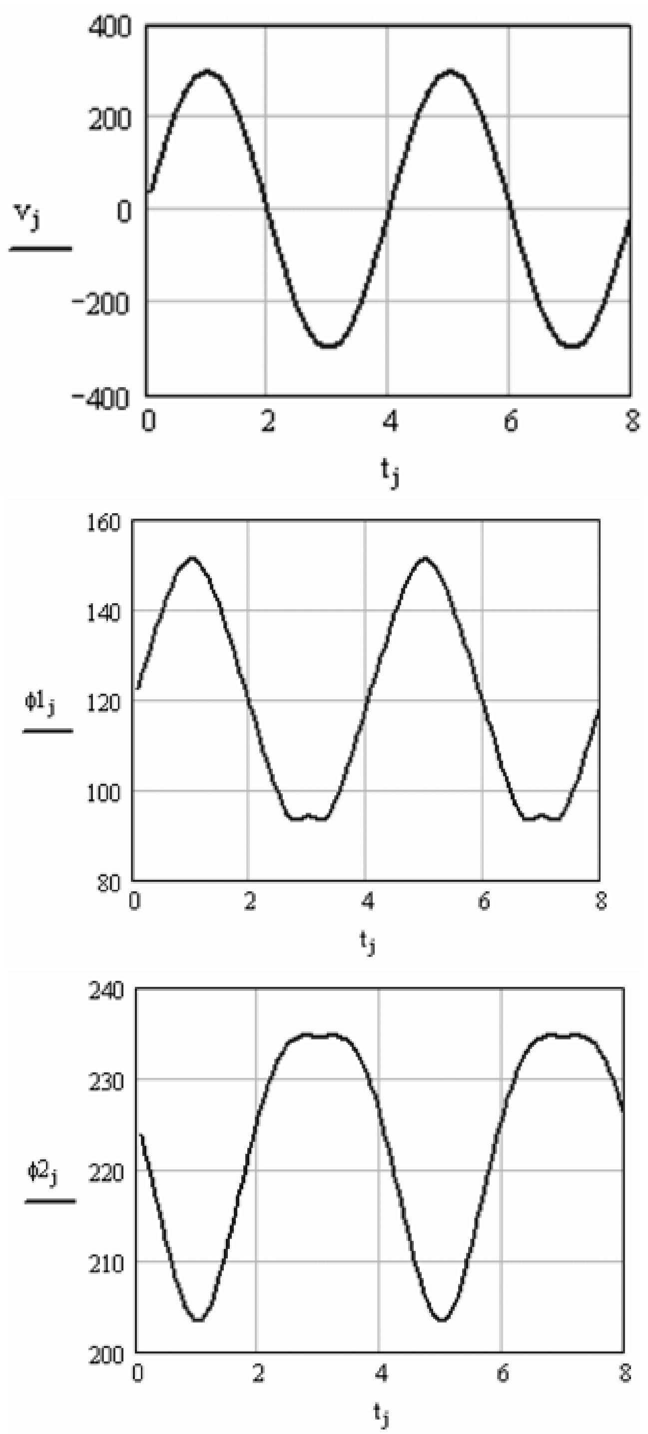

Fig. 10 Variation diagrams of velocity and angles φ1 and φ2 versus time

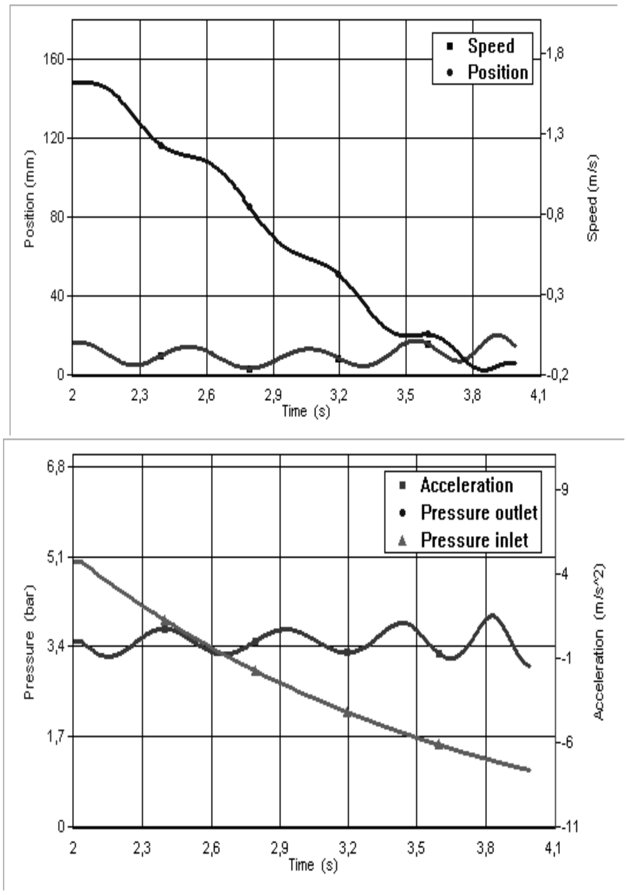

Fig. 11 Variation of the muscle position, speed and acceleration versus time

It can be noticed that the speed of the muscle free end, and implicitly of the sliding block has small variations, thus not being rigorously constant. These variations can however be easily removed by including a throttle in the pneumatic actuation circuit.

V. CONCLUSIONS

The proposed rehabilitation equipment benefits from a cost efficient, simple and robust construction, being easy to use by persons affected by dysfunctions of the bearing joints. Another major advantage of the proposed system is the utilized as source of energy, namely air that completely absorbs all shocks occurring at the ends of the stroke. The current, electro-mechanically actuated rehabilitation systems introduce shocks upon reversion of the sense of motion, thus causing discomfort to the user.References

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