POLIMODULAR MECHATRONIC ORTHOTIC SYSTEM FOR RECOVERY OF LOWER LIMBS IN PAEDIATRIC ORTHOPAEDICS

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1. INTRODUCTION

In pediatric orthopedics there are cases where the limbs, especially the pelvic ones, being subject to forces directly proportional to mass ($F = mxg \mid g = 9.8\ m/s^2$), are presenting joint stiffness, congenital, as in arthrogryposis, or as a result of severe traumatic or infectious diseases, such as in osteomyelitis cases.

Although congenital stiffness is detected early, from the first week of life, there is no effective way to apply supported physical therapy, able to avoid severe evolutionary complications, these ones being sometime disastrous. Artrogryposis (congenital multiplex arthrogryposis) is a muscular-neurological disorder affecting the functioning of joints and it is the generic term used to refer to a group of diseases that hav e in common the presence of joint stiffness.

Current methods of physical therapy, applied from the first days after birth apparently give the impression of recovery, but as the infant grows, vicious positions become increasingly obvious until the involved joints get stiff to fixed, preventing reduction to normal. . Major cause of arthrogryposis is fetal akinesia, which may be due to fetal abnormalities (neurological abnormalities, muscle, connective tissue or mechanical limit of fetal movements) or to maternal diseases (infection, trauma, drug use or other maternal conditions).

Clinical manifestations associated to joint contractures may vary from case to case, but generally there are certain common characteristics: the affected extremities are spindle or cylindrical, covered by soft, smooth skin, with poor subcutaneous tissue and dermal crests

Fig.1. Clinical aspect of a stiff knee joint blocked in a 90 degrees flexion in multiple congenital artrogryposis. Visible altering of the anatomy of the knee relief and muscular atrophy

Fig.2. Radiological findings are represented by a narrow joint space. Bone ends are practically in intimate contact, the shadow of the periarticular soft tissue is increased in volume and of globular appearance.

Joints may become stiff due to trauma, either by directly affecting the joint (intra- or transarticular fractures, damages of the joint capsule or of the tendinous-ligamentous apparatus) or indirect trauma and its effects, imposing resting for a variable time period (dynamic abstention / immobilization).

In all these cases, in order to avoid these severe sequels, it is useful to use a way to combine minimal invasive surgery with a quasi-continuous recovery allowing mobilization of the joints to avoid arthritis.

2. MECHATRONIC ORTHOTICS IN ARTHROGRYPOTIC JOINTS

Polimodular mechatronic orthotic system refers and focuses on a complex configuration that combines mechanical and electronic components by computerized control, which combined will allow the creation of a new generation of simplified, more economical, more efficient, safer and more versatile orthotic devices. This will effectively combine biological side with the mechanical one in shape of attachable and removable devices of exoskeleton type. The role of the exoskeleton will be one both therapeutic as well as augmentation of existing motor function, but diminished in patients suffering from locomotion deficits localized to the musculoskeletal apparatus.

The operating principle of these orthotic systems designed to improve mobility of joints of these patients is based on the classic axiom "function creates the organ". In case of artrogryposis, research has shown that lack of movement in the joints due to either intrinsic (oligohydramnios or architectural fetal malformations that prevents active fetal movements) or extrinsic (neuromuscular with muscular atrophy, pure neurological or periarticular connective tissue suffering), causing joint stiffness.

One mean to improve joint function is represented by a mechatronic orthotic individualized system for each patient and each segment involved bringing together the highest proportion in the classical principles of treatment (orthotics, physiokinetotherapy, occupational therapy).

This system allows informational integration of data and goniometrical control of joint's ranges of motion, allowing the performing of therapeutic computerized gradable exercises. The modular system will comprise consecutive joints (hip, ankle, foot) and will function according to a hierarchical architectural control of the movement: an ultimate level of control (selection of the desired movement), a strategic control level (elementary division of movements), a tactical level control (desired motion distribution in each joint) and a level of control over the execution (a synergistic kinematic chain).

The constructive mechanical component is associated with an electronic command and control component, as well as dedicated software, specific to the motion algorithm used to allow sufficient flexibility to the needs of different stages of the applied recovery treatment.

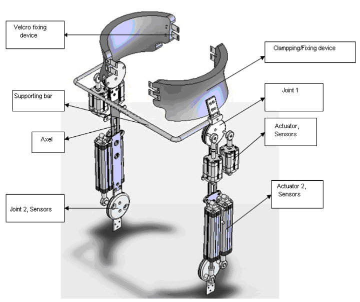

Fig.3. Functional model, constructive component

The main functions of orthotic system are:

- **active** - achieving flexion-extension movements of the targeted joint;
- **passive** - imposing of a resistant torque when the patient performs the flexion-extension movement.

3. KINEMATICAL SCHEMES OF THE ORTHOTIC SYSTEM

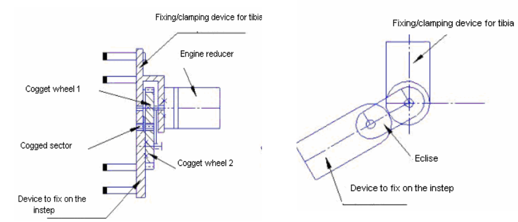

Fig.4. Ankle module

Component modules of the orthotic system (*fig.4, 5 and 6*) are designed to perform the listed functions. In terms of kinematics and construction, the modules are designedfor the three joints: ankle, knee and hip, being relatively the same, namely:

- the use of electric rotation actuators (stepper motors or DC motors)

- the using of polycentric joints with two axes of rotation, the involved joint axis intersecting the circle gear diameter of gear sectors; the joint allowing the mechanical limiting or position sensors to limit values for angle of rotation;
- the existence of insurance linings to ensure the gear anthraxes;

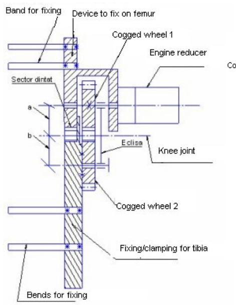

Fig.5. Knee Module

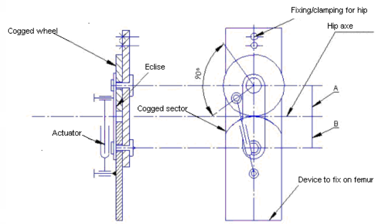

Fig.6. Hip Module

- the possibility of implementing an *i = a / b* transmission ratio, *a* and *b* being the division radii of the toothed sectors;
- the existence of dimensional adjustments for grips, in order to obtain a high degree of compatibility for most patients.

Latches are specific to each module and are anatomical morphological formed to clamping adjacent areas. The grip should be firm, to train correctly affected bone segments without damaging areas where it is gripped. In the orthotic part there are two fasteners that connect the bone segments above, respectively, below the joint, allowing its mobilization. The fixing of the two grips of the orthotic module must ensure concentricity of the axis of rotation of the mechatronic orthosis with the axis of joint of rotation of the lower limb undergoing treatment and guiding of the bone segments in the plane of rotation. In order to prevent chondrolysis injuries by overloading, there will be intraarticular protective solutions injected, based on lysozyme, alfa-chemotripsin or commercial medicine like Synvisc.

Technical secifications:

a. Ankle module:

- Gear motor: type 30 / 1, Φ = 30 mm to the reducer and Φ = 30 mm to the motor;
- Rotation angle: -30° to + 40°, adjustable;
- Electric motor rotation speed: 5000 rpm;
- Transmission gear ratio: 415:1;
- Rotational speed at the exit of the gear: max. 12 r / min, adjustable;
- Active couple working out of the gear: max. 6 Nm;
- Supply voltage: 24 VDC;
- Limiting of the angle of rotation: electronic and mechanical;
- Adjusting the rotational speed: electronically.

b. Knee module:

- Gear motor: type 38 / 2, Φ = 38 mm to reducer and Φ = 30 mm to the motor;
- Rotation angle: -30 to + 90°, adjustable;
- Electric motor rotation speed: 5000 rpm;
- The transmission gear ratio: 415:1;
- Rotational speed at the exit of the gear: max. 12 r / min, adjustable;
- Active couple working out of the gear: max.15 Nm;
- Supply voltage: 24 VDC;
- Limiting the angle of rotation: electronic and mechanical;
- Adjusting the rotational speed: electronically.

c. Hip module:

- Gear motor: type 38 / 2, Φ = 38mm to reducer and Φ = 30mm to the motor;
- Rotation angle: -15° to + 45°, adjustable;
- Electric motor rotation speed: 5000 rpm;
- The transmission gear ratio: 415:1;
- Rotational speed at the exit of gear: max. 12 r / min, adjustable;
- Active couple working out of gear: max.15 Nm;
- Supply voltage: 24 VDC;
- Limiting the angle of rotation: electronic and mechanical;
- Adjusting the rotational speed: electronically.

4. JOINT DYNAMIC CALCULATION

The calculation is exemplified in the joint most frequently affected and treated - the knee joint, as illustrated in the calculation scheme (*Fig.7 and 8*). The coordinate system is considered as an orthogonal trihedral oriented as in the figure, the points O and O_1 of the joint orthosis define the OO_1 knee axis of rotation.

The study is made in the OR_{zy} midfoot plane with T_{yz} mobile point.

T_{yz} point parameters:

- positioning vector $\overline{ORT_{yz}}$ of the R module = $|ORT_{yz}|$
- angular velocity in OR_{yz} plane: $\omega_{yz} = \dot{\theta} = ct.$
- angular acceleration: $\dot{\omega}_{yz} = \ddot{\theta}$
- angle position: θ
- area covered by the point on the tibia: s = $T_y T_{yz}$.

There will be a rotating movement in an ORT_{yz} medium plane around a OR point.

Equations of motion in uniform circular motion:

$$S = 0RT_{YZ} = R\theta = R\omega t$$

$$v = \dot{S} = R\omega$$

$a_\tau = \ddot{S} = O$, angular acceleration.

$a_\gamma = \frac{\dot{S}^2}{R} = R\omega^2$, acceleration.

Non-uniform circular motion equations:

$$v = \dot{S} = R\dot{\theta} = R\omega$$
$$a_\tau = \ddot{S} = R\ddot{\theta} = R\dot{\omega}$$
$$a_\gamma = R\omega^2$$
$$a = \sqrt{a_\tau^2 + a_\gamma^2} = R\sqrt{\dot{\omega}^2 + \omega^4}$$

Tibia to the femur in the knee motion axis is the movement of a solid.

Equations of motion:

- movement relates to the Orxyz axis system with fixed Orx axis (rotation axis).

Tibia to the femur performs a rotation movement around the knee axis. In order to study the tibia to the femur movement consider the Orxyz mobile tried jointly with the tibia whose rotation axis is Orx and the $O_1Rx_1y_1z_1$1 fixed tried whose origine O_1R coincides with OR and whose O_1Rx_1 axis coincides with the Orx axis. The angle axes θ (O_1Ry_1, Ory) are marked with.

Movement is defined by: $\theta = \theta(t)$ with one degree of freedom.

Trajectories of various points around the Orx axis are circles centered on the axis of knee rotation, and are dependent movements between them. Out of the distribution of velocities and accelerations results links between movement points.

Speed and acceleration of any point on the tibia are:

$$\bar{v} = \bar{v}_0 + \bar{\omega} \times \bar{R} \qquad (1)$$
$$\bar{a} = \bar{a}_0 + \bar{\dot{\omega}} \times \bar{R} + \bar{\omega} \times \bar{\dot{R}} \qquad (2)$$

in the given situation: $\bar{v}_0 = 0$; $\bar{a}_0 = 0$; $\omega_x = \dot{\theta}$; $\omega_y = 0$ si $\omega_z = 0$

Projections on the velocity axes $\bar{v}$ are:

$$\begin{cases} v_x = 0 \\ v_y = -\dot{\theta} \cdot z = -\omega z \\ v_z = \dot{\theta} y = \omega y \end{cases} \qquad (3)$$

$$v = \sqrt{v_y^2 + v_z^2} = \dot{\theta}\sqrt{y^2 + z^2} = \dot{\theta} \cdot R \qquad (4)$$

Projections on the axes of acceleration $\bar{a}$ are:

$$\begin{cases} a_x = 0 \\ a_y = -\omega_x^2 - \dot{\omega}_x z = -\dot{\theta}^2 \cdot y - \ddot{\theta} z \\ a_z = -\omega_x^2 z + \dot{\omega}_x y = \ddot{\theta} y - \dot{\theta}^2 \end{cases} \qquad (5)$$

Hence: $a = R\sqrt{\dot{\omega}^2 + \omega^4}$ (6)

Forces torsos in the OR point acting on the joint:

$$\tau(\bar{F}) = (\bar{R}\ ; \bar{M})$$

Where: $\bar{R}$ the forces resultant in the OR point.

$\bar{M}$ forces moment in the OR point.

Linking forces of theand points, O and O'' the reactions are $\bar{N}$ and $\bar{N'}$ also unknown. To obtain the parameter $\theta = \theta(t)$ we apply to the angular momentum axis theorem related to the axis ORx_1 : $\dot{K}_x = M_x$

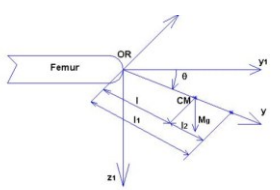

Fig.8.The calculation of the reactions in the joint.

Where: K_x - angular momentum projection $\bar{K}$ related to OR on the axis Ox_1

M_x - projection of total moment $\bar{M}$ of forces on the Ox_1 axis.

From: $K_x = j_{xx}\omega$ and $\omega = \theta'$ and results

$$j_{xx}\ddot{\omega} = M_x \qquad (7)$$

The calculation of the reactions in the *OR* point *(fig.8.)*

$$M\left[\bar{\dot{\omega}} \times \bar{\rho} + \bar{\omega} \times (\bar{\omega} \times \bar{\rho})\right] = \bar{R} \qquad (8)$$

Where:
- M - Weight of the tibia and foot
- $\bar{\rho}$ - Distance from *OR* to the center of gravity for the mass M
- $\bar{\omega}$ - Angular velocity of the center of mass
- $\bar{\dot{\omega}}$ - Acceleration of the mass center
- $\bar{R}$ - Resultant forces in *OR*

Tibia and foot movement related to the femur in the knee joint movement is similar to a physical pendulum. If one writes the equation of motion in the plane z_1ORy_1 around the *OR* point:

$$j_{yy} = -M_y l \cos\alpha$$

and considers the assembly as a whole bar with the center of mass in *CM*, length *l* and l_2 (arm length $l+l_2$) and *D* diameter, the reactions in *OR* may be calculated:

Reactions in *OR* are:

$$\begin{cases} R_x = 0 \\ R_y = -M\,g\sin\theta - \omega^2 M\,l \\ R_z = M\,g\cos\theta + \omega M\,l \end{cases} \quad (9)$$

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