Distributed variable stiffness joint assist mechanism based on laminated structure

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Abstract
Exoskeleton technology is more and more widely used in military, human rehabilitation, and other fields, but exoskeleton assisting mechanisms have problems such as high quality, concentrated driving sources, and poor flexibility. This article proposes a distributed variable stiffness joint power-assisted mechanism based on a laminated structure, which uses a giant magnetostrictive material as the driving source and the variable stiffness source of the structure. The distributed driving is realized by multiple driving units connected in series and parallel. Firstly, the drive unit stiffness matrix is deduced, and the expression equations of the cascaded total stiffness matrix of the drive module are obtained. After the simulation study, the curve of the stiffness of a single drive unit with a magnetic field and the stiffness of multiple drive units connected in series and parallel are in the absence of the magnetic field. The change curve of the stiffness of the booster module with the number of drive units under the excitation and saturation magnetic field excitation conditions is to achieve the effect of dynamically controlling the structural stiffness of the drive unit by controlling the size of the magnetic field and to obtain a general formula through data fitting. The number of drive units required under a fixed magnetic field excitation can ensure that the error is within 5%. The research results lay the foundation for further analysis of the distributed variable stiffness joint assist technology.

Keywords
Laminated structure, distributed drive, variable stiffness, drive unit

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Introduction
At present, exoskeleton assist technology is used more and more widely in military and human rehabilitation treatment. Exoskeleton assist technology is usually driven by DC servo motor, hydraulic pressure, pneumatic pressure, flexible cable, and so on, all of which are centralized drive sources. The high stiffness characteristics of centralized drive source may cause harm to users, so the research of distributed and variable stiffness drive structure and method has also attracted the attention of scholars.¹⁻⁵ Distributed drive structure is mainly used in scenarios where power transmission is difficult. Distributed drive makes the power assist mechanism more compact and can improve the drive efficiency and response speed. Variable stiffness is mainly used in various scenarios that need flexible mechanical structure, and it is the main measure to improve the flexibility of the power assist mechanism. The variable stiffness structure is easy for users to wear and reduces the harm of high stiffness to the human body.⁶ Many scholars have reported the research on variable stiffness and distributed drive. Wang Jun of the University of the

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Chinese Academy of Sciences has researched variable-rigidity rope-driven joint modules. By connecting different numbers of variable-rigidity devices, variable speed drive in series, a single-degree-of-freedom, and two-degree-of-freedom rope-driven joint module with a wide range of stiffness variations has been obtained but failed to effectively change the stiffness performance test of the stiffness rope-driven joint module.7 Ronald Van Ham et al. designed the robot Veronica by using the spring deformation direction to make a certain angle with the external force and adjusting the stiffness by adjusting the spring pretension, but the walking was not stable.8 Harbin Institute of Technology Yike Shengli uses the Deutsches Zentrum für Luft-und Raumfahrt-Floating Spring Joint (DLR-FSJ) variable stiffness principle to achieve joint stiffness changes, but the structure is complex and the flexibility needs to be improved.9 Metta10 of the Italian Institute of Technology, etc. has designed a compact variable stiffness joint based on Series Elastic Actuation (SEA), but the number of motors required is large. Thirty-eight motors are required, only for the forearm of the Deutsches Zentrum für Luft-und Raumfahrt (DLR) arm system; the amount of data processing is large and the control is difficult. In recent years, flexible drives have become the focus of scholars' research that has the characteristics of lightweight and good human-computer interaction. However, due to movement, skin slippage and other reasons caused by sensor offset, resulting in inaccurate control.11 At present, distributed variable stiffness joint assist is still a big gap in research at home and abroad. Combining variable stiffness with distributed can not only increase the human–computer interaction flexibility of joint assist but also ensure its safety.

In this article, by introducing giant magnetostrictive materials and laminated structures, new variable stiffness and distributed driving principles are proposed. Combining the magnetostrictive material Terfenol-D with the laminated structure is to achieve the principle of variable stiffness of the booster unit when Young’s modulus is different and the magnetic field is excited with different strengths. The distributed drive principle uses a laminated structure to achieve three-degree-of-freedom control of a single drive unit. Finally, multiple drive units are arranged and combined to achieve a distributed drive structure. The assisting principle of the driving unit is to use the angular change and stiffness change generated by the driving unit under the action of the driving material to work together to achieve assistance during the joint motion.

**Drive unit model**

The driving unit proposed in this article is constructed with a laminated structure. The polyimide sheet is made into a specific shape according to the needs of constructing three degrees of freedom, from top to bottom are the upper drive layer, the upper excitation layer, the rotation layer, the channel layer, the lower excitation layer, and the lower drive layer. The structure and connection order of each layer is shown in Figure 1. Each layer is adhered to by DuPont Pyralux LF0100LF acrylic adhesive. Each synthesized drive unit has three degrees of freedom, from left to right are the first degree of freedom, the second degree of freedom, and the third degree of freedom. The action of the degrees of freedom is controlled by the giant magnetostrictive material, as shown in Figure 2. Magnetostrictive materials have the function of converting electromagnetic energy and mechanical energy, and their stiffness and shape will change under the excitation of the magnetic field. The energy density of giant magnetostrictive materials is higher. The magnetostrictive coefficient is larger, which is dozens of times of Fe and Ni, and three to five times of piezoelectric ceramics.12 Therefore, giant magnetostrictive materials are used to design the joint assist mechanism.

**Drive unit model working principle**

The working principle of the drive unit model consists of two parts, one is the principle of variable stiffness and the other is the principle of the distributed drive. The variable stiffness principle guarantees the safety of the drive unit’s assistance; the distributed drive principle guarantees that each drive unit can be independently controlled to ensure the flexibility of its human–computer interaction. The two together works to achieve variable stiffness distributed joint assistance.
Variable stiffness principle

The magnetostrictive material Terfenol-D stiffness is expressed by Young’s modulus, and its effect is used to achieve the structural variable stiffness. According to the first type of piezomagnetic equation, Young’s modulus can be obtained under different magnetic field strengths. The known parameter variables are presented in Table 1.

\[
\begin{align*}
\varepsilon &= \frac{\sigma}{E_y} + d_{33}H \\
B &= d_{33}^* \sigma + \mu H \\
E_y &= \frac{\sigma}{\varepsilon - d_{33}H}
\end{align*}
\]

Among them, \(\varepsilon\) is the strain, \(\sigma\) is the stress, \(E_y\) is Young’s modulus of the magnetostrictive material under the action of the magnetic field strength \(H\), \(d_{33}\) indicating the compressive magnetic coefficient or the dynamic magnetostriction coefficient, \(H\) indicating the magnetic field strength, \(B\) indicating the magnetic induction intensity, and \(d_{33}^*\) indicating the magnetic machine coefficient or the dynamic inverse magnetostriction coefficient can be considered as the magnetic permeability of the magnetostrictive material under constant stress by considering only the magnetic machine coupling problem in the longitudinal direction of the magnetostrictive material. In terms of the relationship between the magnetic field strength and Young’s modulus, Sun Le of Lanzhou University obtained theoretical and experimental results of Young’s modulus–magnetic field strength under different pre-pressures at a temperature of \(T = 20^\circ C\) as shown in Figure 3. It can be seen that when determining the temperature and the pre-pressure, Young’s modulus of the giant magnetostrictive material can be controlled by changing the magnetic field strength, which lays a foundation for precise control. When Young’s modulus is changed, the ability of the mechanism to resist deformation changes, there by achieving variable stiffness. And due to the change of the magnetic field strength, the Terfenol-D Young’s modulus changes with the change of the stiffness of the drive unit. During this process, the magnetic field strength is controllable, so the stiffness of the drive unit is also controllable; it is not only the two states of no magnetic field excitation and saturation magnetic field excitation. There are multiple excitation states between the two excitation states, that is, multiple stiffness variations.

Distributed drive principle

Distributed drive is an assist mechanism composed of \(n\) multiply by \(m\) drive units arranged in series. Each drive unit is connected in series or parallel by adhesion or tendon, but the excitation coil of each drive unit is powered separately, so each drive unit can control individually or combine multiple drive units into a regional stiffness module, and each area is individually powered to control the magnetic field to achieve a distributed drive effect of the area, as shown in Figure 4.
Research on stiffness of distributed variable stiffness joint assist mechanism

Drive unit stiffness matrix

Two factors affecting the stiffness of the drive unit: one is the elastic modulus of the material of the drive unit, and the other is the structure of the drive unit. When a magnetic field is applied to a magnetostrictive material, the elastic modulus of the material becomes large, and at the same time, the structure of the drive unit changes due to the longitudinal magnetostriction of the magnetostrictive material, and the stiffness of the drive unit changes. Because the driving unit is small enough and only one end is fixed, the driving unit can be equivalent to a beam, and the stiffness matrix of the driving unit can be obtained by solving the stiffness matrix of the beam. The element has three nodes (degrees of freedom at both ends and degrees of freedom at the midpoint). The definition is introduced as follows:

\[
\{F\}^e = [F_{x1} \ F_{y1} \ F_{z1} \ M_{x1} \ M_{y1} \ M_{z1} \ F_{x2} \ F_{y2} \ F_{z2} \ M_{x2} \ M_{y2} \ M_{z2} \ F_{x3} \ F_{y3} \ F_{z3} \ M_{x3} \ M_{y3} \ M_{z3}]^T \quad (3)
\]

\[
\{\Delta\}^e = [\mu_1 \ \nu_1 \ w_1 \ \theta_1 \ \theta_1 \ \theta_1 \ \mu_2 \ \nu_2 \ w_2 \ \theta_2 \ \theta_2 \ \theta_2 \ \mu_3 \ \nu_3 \ w_3 \ \theta_3 \ \theta_3 \ \theta_3]^T \quad (4)
\]

Each node of the driving unit has a 6 × 1 6-by-1 order force vector and a dual displacement vector:

\[
\{F_i\}^e = [F_{xi} \ F_{yi} \ F_{zi} \ M_{xi} \ M_{yi} \ M_{zi}]^T \quad (5)
\]

\[
\{\Delta_i\}^e = [\mu_i \ \nu_i \ w_i \ \theta_i \ \theta_i \ \theta_i]^T \quad (6)
\]

In the formula, \(i = 1, 2, 3\). And \(M_{xi}, M_{yi}, \) and \(M_{zi}\) are the torques of the three planes xy, xz, and yz, respectively. That is, the force vector and displacement vector at the node of the driving unit are as follows:

\[
\{F\}^e = \{(F_1)^e \ (F_2)^e \ (F_3)^e\}^T \quad (7)
\]

\[
\{\Delta\}^e = \{\{\Delta_1\}^e \ {\Delta_2\}^e \ {\Delta_3\}^e\}^T \quad (8)
\]

According to the theory of linear elasticity with small deformation, the effects of axial force \(F_i\) and bending forces \(F_y, F_x, M\) are independent of each other and there is no mutual coupling relationship, so the stiffness equation can be directly “assembled” by the stiffness equation of the axial force element and the plane bending element equation. The derivation and assembly of the stiffness matrix are mainly obtained through the assistance of MATLAB (https://www.mathworks.com/). It is used for data analysis and mathematical model derivation software. Its stiffness equation is as follows:

\[
\{F\}^e = [k]^e \{\Delta\}^e \quad (9)
\]

where \(\{F\}^e\) and \(\{\Delta\}^e\) are both 18 × 1 order vectors, and the stiffness matrix \([k]^e\) is a 18 × 18 square matrix.

Because the driving unit has three nodes, the stiffness matrices between 1,2 and 2,3 nodes are obtained first and then they are assembled into an overall stiffness matrix. The element stiffness matrix of spatial beam element in the local coordinate system is as follows:

\[
K(12 \times 12^e) = \begin{bmatrix}
\frac{EA}{T} & 0 & 0 & 0 & 0 & 0 & -\frac{EA}{T} & 0 & 0 & 0 & 0 & 0 \\
0 & \frac{12EI_y}{I^2} & 0 & 0 & 0 & -\frac{6EI_y}{I^2} & 0 & -\frac{12EI_y}{I^2} & 0 & -\frac{6EI_y}{I^2} & 0 & -\frac{6EI_y}{I^2} \\
0 & 0 & \frac{12EI_z}{I^2} & 0 & 0 & 0 & 0 & 0 & -\frac{6EI_z}{I^2} & 0 & 0 & 0 \\
0 & 0 & 0 & \frac{GJ}{I} & 0 & 0 & 0 & -\frac{GJ}{I} & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & \frac{6EI_z}{I^2} & 0 & 0 & 0 & 0 & -\frac{2EI_z}{I} & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & \frac{4EI_z}{I^2} & 0 & 0 & 0 & 0 & -\frac{2EI_z}{I} & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & \frac{6EI_z}{I^2} & 0 & 0 & 0 & 0 & \frac{2EI_z}{I} \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{EA}{T} & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{12EI_y}{I^2} & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{6EI_y}{I^2} & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{6EI_y}{I^2} & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{4EI_y}{I^2} \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{4EI_y}{I^2} \\
\end{bmatrix} \quad (10)
\]
Among them, the bending stiffness coefficient \( i = \frac{EI}{l} \), where \( I \) is the moment of inertia and \( l \) is the length of the drive unit. The transformation matrix of local and global coordinates is as follows

\[
T^e = \begin{bmatrix}
\lambda (3 \times 3) & 0 & 0 & 0 \\
0 & \lambda (3 \times 3) & 0 & 0 \\
0 & 0 & \lambda (3 \times 3) & 0 \\
0 & 0 & 0 & \lambda (3 \times 3)
\end{bmatrix}
\] (11)

\([k]^1, [k]^2\) are obtained by multiplying the element stiffness matrix formula in the local coordinate system with the transformation matrix of local coordinates and global coordinates. Divide \([k]^1, [k]^2\) into blocks, and the processing results are as follows

\[
[k]^1 = \begin{bmatrix}
[k_{11}]^{1 \times 6 \times 6} & [k_{12}]^{1 \times 6 \times 6} \\
[k_{21}]^{1 \times 6 \times 6} & [k_{22}]^{1 \times 6 \times 6}
\end{bmatrix}
\] (12)

\[
[k]^2 = \begin{bmatrix}
[k_{22}]^{2 \times 6 \times 6} & [k_{23}]^{2 \times 6 \times 6} \\
[k_{32}]^{2 \times 6 \times 6} & [k_{33}]^{2 \times 6 \times 6}
\end{bmatrix}
\] (13)

Then the assembly result of the overall stiffness matrix of the driving unit can be expressed by \([k]^1, [k]^2\)

\[
[k]^e = \begin{bmatrix}
[k_{11}]^{1 \times 6 \times 6} & [k_{12}]^{1 \times 6 \times 6} & 0 \\
[k_{21}]^{1 \times 6 \times 6} & [k_{22}]^{1 \times 6 \times 6} + [k_{22}]^{2 \times 6 \times 6} & [k_{23}]^{2 \times 6 \times 6} \\
0 & [k_{32}]^{2 \times 6 \times 6} & [k_{33}]^{2 \times 6 \times 6}
\end{bmatrix}
\] (14)

\(\{F\}^e = [k]^e \{\Delta\}^e\) can be written as follows

\[
\begin{bmatrix}
\{F_1\}^e \\
\{F_2\}^e \\
\{F_3\}^e
\end{bmatrix} = \begin{bmatrix}
[k_{11}]^e & [k_{12}]^e & [k_{13}]^e \\
[k_{21}]^e & [k_{22}]^e & [k_{23}]^e \\
[k_{31}]^e & [k_{32}]^e & [k_{33}]^e
\end{bmatrix} \begin{bmatrix}
\{\Delta_1\}^e \\
\{\Delta_2\}^e \\
\{\Delta_3\}^e
\end{bmatrix}
\] (15)

Because the drive unit has a variable stiffness structure, the stiffness values under different magnetic field driving conditions are obtained through simulation and brought into the stiffness matrix, and the stiffness matrix results can be obtained.

The \( n \) drive units are connected in series, parallel, and series-parallel cascade to form a booster mechanism by bonding or tendons. The connection between the units will generate viscous damping \( c \) and viscous damping force \( -cx \). The unit is excited by a magnetic field and the output force is \( kx \) and subjected to the inertial force \( mx \). The force in the drive module can be written as follows

\[
F_{\text{total}} = kx + cx + mx
\] (16)

The physical properties of magnetostrictive materials are viscoelastic. The damping matrix can be expressed as

\[
C = K\tau, \quad \text{where} \quad \tau = \frac{c}{E}
\] (17)

The mass matrix is obtained after the inertial force is equivalent to the static force of the node. Commonly used mass matrix representation methods include centralized mass matrix and consistent mass matrix. In this article, the element mass matrix is derived by the same method as the derived stiffness matrix, that is, the uniform element mass matrix is used. The solution method is similar to the element stiffness matrix solution, and each node has translational and rotational degrees of freedom, so it can be assumed that the diagonalized stiffness matrix as follows

\[
[M]^e = \begin{bmatrix}
M_L^1 \\
M_L^2 \\
\vdots \\
M_L^n
\end{bmatrix}
\] (18)

To sum up, \( F_{\text{total}} \) can be expressed as follows

\[
F_{\text{total}} = [k]^e \{x\}^e + [C]^e \{\dot{x}\}^e + [M]^e \{\ddot{x}\}^e
\] (19)

where 18 in \([k]^e_{18 \times n}, [C]^e_{18 \times n}, [M]^e_{18 \times n}\) stands for 18 rows of each stiffness matrix (three degrees of freedom of the drive unit, each degree of freedom has three translation vectors and three rotation vectors), and \( n \) represents the number of series and parallel drive units.

**Simulation of stiffness of drive unit**

The driving unit is equivalent to a beam, and the driving unit bears a uniform load during the boosting process. Therefore, the change in deflection of the beam can be used to represent the change in stiffness during simulation. First, the change of the deflection is obtained and then the change of the stiffness of the driving unit is calculated by the formula.

The \( A \) end is fixed and the \( B \) end is free, as shown in Figure 5. The stiffness matrix of the drive unit and the total force expression are obtained above. The specific relationship between the stiffness of the booster mechanism and the number of drive units can be obtained through simulation. It is more helpful to expand the booster mechanism. The \( z \) axis stiffness value is examined to verify the feasibility of the variable stiffness booster mechanism.

The equation of the curve around the beam under uniform load is given as follows

\[
y = -\frac{qx^2}{24EI} (x^2 - 4lx + 6l^2)
\] (20)

When \( x = l \), the maximum deflection generated by the driving unit is as follows
where $q$ represents the uniform load acting on the drive unit, $l$ represents the length of the drive unit, and $E_{(T+P)}$ represents Young’s modulus of the material of the drive unit, which is Young’s modulus of the coupling between the giant magnetostrictive material and the polyimide material, $I$ represents the moment of inertia of the cross section of the drive unit, $I = \frac{ab^3}{12}$, where $a$ represents the width of the drive unit and $b$ represents the thickness of the drive unit.

To make the giant magnetostrictive material have a significant $\Delta E$ effect, pre-pressure is usually added to the giant magnetostrictive material. The curve of the Terfenol-D Young’s modulus with magnetic field strength when the pre-pressure is $\sigma = -27.37$ MPa is shown in Figure 6.

The above derivation was simulated and verified through analysis system (ANSYS) Workbench (https://www.ansys.com/). It is the collaborative simulation environment proposed by ANSYS, which can analyze the static mechanics, dynamics, electromagnetic field, and coupling field of complex mechanical systems. When no magnetic field excitation and different intensity magnetic field excitation were applied, a surface force of $100N$ was applied to the upper driving layer, which is equivalent to applying a uniform load of $q = 2 \times 10^6 N/m^2$ on the surface. By using the probe function in Ansys Workbench, to obtain the change in the $z$-direction displacement of the rightmost side of the drive unit when no magnetic field excitation and different intensity magnetic field excitation are applied, this displacement amount is the maximum deflection of the drive unit, and according to formula (28), calculate the change curve of $E_{(T+P)}$ with the magnetic field $H$, as shown in Figure 7.

According to the above figure, it can be seen that the stiffness value of the drive unit changes significantly when the magnetic field is not excited and after the saturated magnetic field is excited. By comparison, it can be concluded that the stiffness of the drive unit has increased by $808.1\%$. According to the curve, the curve can be divided into three sections: the magnetic field is from nothing, the magnetic field is from small to $75$ KA/m, and the magnetic field is from $75$ KA/m to the saturated magnetic field.

The drive unit can be applied to different working situations according to the three situations. The magnetic field has a rapid change in stiffness from none to sometimes, which can be applied to the moment when the human muscle has a strong explosive force; the magnetic field gradually decreases from a small magnetic field to a period during which the stiffness can be reduced. During the deceleration phase of human muscles, the magnetic field is from $75$ KA/m to a saturated magnetic field, and the stiffness of the drive unit slowly increases, which can be applied to the lifting phase of the human body carrying heavy objects. According to the analysis above, it is found that the drive unit can achieve variable stiffness under the action of the excitation magnetic field and meet the design requirements.

**Stiffness characteristics of distributed power-assisted mechanism**

Combined with the derivation of the stiffness characteristics of the single drive unit above to study the stiffness of the distributed booster mechanism, there are seven cases of distributed drive expansion: $x$-direction one-dimensional expansion; $y$-direction one-dimensional expansion; $z$-direction one-dimensional expansion; $x$, $y$-direction two-
dimensional expansion; $x$, $z$ two-dimensional expansion; $y$, $z$ two-dimensional expansion; and $x$, $y$, $z$ three-dimensional expansion. Take three typical situations of the seven expansion methods for simulation research: the drive unit $z$ expands in one dimension, the drive unit $x$ expands in one dimension, and the drive unit expands in two directions in $x$ and $y$. The relationship between the stiffness of the extended drive module and the number of drive units connected in series and through simulation is obtained through simulation. A general formula for the stiffness and the number of drive units is obtained by data fitting. The formula can be used to inverse the number of drive units required when different stiffness is required.

When the stiffness of the single-layer drive unit cannot meet the requirements, multiple drive units can be connected in parallel in the $z$-direction. The way is to glue the upper drive layer of the lower drive unit and the lower drive layer of the upper drive unit together with DuPont acrylic adhesive. And when the drive module is placed at a joint such as an arm to assist, the boost area of a single drive unit is far from meeting the needs, so the drive units need to be connected in series or two-dimensional spread to a large-area series booster mechanism. The connection method is the rear face of the previous drive unit bond or adds tendons to the front face of the latter drive unit for connection.

Compare the change in the stiffness of the booster mechanism with and without magnetic field excitation and obtain the $z$-direction displacement through the probe, that is, the deflection value of the parallel booster. The relationship between the number of drive units and the deflection value under three typical expansion modes is presented in Table 2.

The relationship between the deflection and the number of units under the conditions of $z$-direction one-dimensional
follows deflection and the number of units under the conditions of variable stiffness requirements.

According to this relationship, the variable stiffness of the power-assisted drive module can be calculated when multiple drive units are connected in series and series–parallel combination without excitation magnetic field or saturated magnetic field in the later period, and the required number of series drive units can be reversely derived through variable stiffness requirements.

By analyzing the combination of the driving unit in one dimension and driving elements in two directions $x$ and $y$, the general relationship between the change in deflection and the number of series and parallel connections can be obtained. According to Equation 21, the change of the assist mechanism $F_{\text{pull}}$ with the number of driving units can be calculated, and the feasibility of the variable stiffness of the series–parallel driving module is further verified.

### Verification

#### Verification of arm movement assistance

When the human forearm supports a heavy object, the forearm stays fixed near the shoulder end. The forearm pull drives the movement of the forearm to generate a moment $M$ at the position of the elbow joint. The downward gravity and force diagram is shown in Figure 9. The assistance mechanism is used to test the effect of the human
body assisting and alleviating the fatigue of the joint
machine muscle when the arm lifts a weight of 10 kg, that
is, the ability to reduce the muscle strength.

The average length of the upper arm and the lower arm
is 328 mm and 312.8 mm, respectively, and the muscle
strength is normal five-grade muscle strength. The bio-
logical structure of arm muscles is complex, and the Any-
body (https://www.anybodytech.com/) software platform
is used to build the skeleton and muscle groups of the
human arm and accurately monitor the changes in muscle
strength of the major muscles of the arm. It is a computer-
assisted human ergonomics and biomechanical analysis
software, both ergonomics and biomechanics to calculate
the body’s biomechanical response to the environment. To
reduce the amount of software calculation, the mechanics
of the arm is simplified. Finally, the arm is simplified as
shown in Figure 10. When the human body lifts a heavy
object, the deltoid muscle forces and keeps fixed, and
the forearm flexes and extends in the sagittal plane of the
human body due to the contraction or relaxation of the
deltoid, biceps, triceps, and brachioradialis.

The driving unit is shown in Figure 11 and it is com-
posed of polyimide sheet and Terfenol-D material accord-
ing to the structure as shown in Figure 1. The length, width,
and height of the three driving materials are 2.5 × 1 × 0.4 mm, 1.5 × 1 × 0.4 mm, and 2.5 × 1 × 0.4 mm,
respectively. With the driving source of the driving unit,
the flexible printed circuit board technology is used to
print the coil to get the exciting magnetic field, and the
magnetic field intensity can meet the use requirements.

The driving unit is cascaded into strip and sheet assist-
ing mechanisms according to the length of the arm and is
clung to the backside of the arm through the bandage. To
improve the effect of the booster mechanism, a number of
sheet booster mechanisms are wrapped around the arm to
form a ring booster mechanism, which is pasted on the
tight elbow protector and closely attached to the arm.

Changes in arm muscle strength

During the kinematics calculation of the simplified arm
model, the shoulder node was taken as the origin of the
model coordinate system, the gravity of 10 kg weight was
added to the hand node, and the upward bending arm move-
mantime was defined. The motion angle is 90° and the motion
time is 1 s. A new node is defined at the corresponding
position of the arm model according to the schematic dia-
gram, and the stiffness and disturbance formulas of each
type of assist mechanism are defined in the node para-
eters. Muscle strength analysis was carried out under the
condition of no magnetic excitation (0 kA/m) and magnetic
excitation (160 kA/m), and the data of the change of muscle
strength $F_m$ with time in the process of exercise were
obtained. The parameters of the components of the assist
mechanism are presented in Table 3.

Simulation parameters, load conditions, and boundary
conditions of each type of assist mechanism are the same.
After validated analysis, the maximum muscle force of the
muscle can be obtained through data processing, as pre-
sented in Table 4.

When there is no magnetic field excitation, the main
muscle force of arm flexion movement is provided by
biceps and deltoid muscles, while the other muscle groups
are in a diastolic state. By comparison, it is found that the
average muscle force of the strip-assisted mechanism is
reduced by 9.2% under the saturation magnetic field drive,
and the assistance mechanism plays a small role. Driven by
the saturated magnetic field, the average muscle strength of
the plate-assisted mechanism is reduced by 27.5%, which
plays a good role.
According to the data in the table, it can be found that when the stiffness of the annular assist mechanism changes significantly with or without magnetic excitation, the assisting effect of the joint is significantly different. The comparison results showed that in the absence of magnetic excitation, wearing the annular assist mechanism would cause a certain burden on the arms curvature, and the muscle strength was larger than that of strip and sheet. However, driven by the saturated magnetic field, the average muscle strength decreases by 57.9%, which plays an excellent helping role, which proves that the ring assist mechanism has an obvious helping effect and high feasibility.

The variation of the arm’s load capacity was analyzed with the magnetic field intensity and the load capacity of the arm was reversely calculated under the stress value when the magnetic field intensity is different. The changing curve of arm load capacity with different intensity magnetic field excitation of the assisting mechanism is shown in Figure 13.

With the change of the magnetic field, the stiffness value of the booster mechanism changes and the magnetic...
field intensity in the range of $0 < H < 60$ KA/m; When the stiffness value reaches the lowest near 60 KA/m, the effect is the least. The stiffness value of the assist mechanism reaches the maximum near the saturated magnetic field (160 KA/m), which has the best effect on reducing the muscle strength.

The initial load of the arm is 10 kg, and the load becomes 11.45 kg with an annular assist mechanism without magnetic field excitation, and the load capacity is 30.15 kg with saturated magnetic field excitation. According to the graph, the annular assist mechanism plays an important role in improving the load capacity of the arm.

**Conclusion**

This article assists the mechanism in modeling and principle analysis, derives the stiffness matrix of the drive unit, and simulates and verifies the drive unit’s three different expansion modes. Finally, the simulation validates the effect of the booster mechanism on the improvement of the human skeleton stiffness. The main conclusions are as follows: (1) the derived stiffness matrix of the driving unit satisfies the characteristics of the element stiffness matrix, which proves that the derivation is correct; (2) the simulation and verification of the three typical expansion modes of stiffness and the number of driving units and data simulation. The general formula of the relationship between the two can guarantee that the error is within 5%; and (3) through the simulation of human body assisting simulation, it is verified that the assisting mechanism can meet the assisting requirements, the assisting effect is obvious, and the excitation magnetic field with different strengths can be adjusted to meet the requirements according to the stiffness requirements. However, the interference of the excitation electromagnetic field with the peripheral electronic equipment is not considered, and further research is needed. The study of distributed variable stiffness joint assist in this article provides a reference value for further research on the human exoskeleton.

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