Load-dependent Variable Gearing Mechanism of Muscle-like Soft Actuator

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Abstract

Pennate muscle is characterized by muscle fibers that are oriented at a certain angle (pennation angle) relative to the muscle's line of action and rotation during contraction. This fiber rotation amplifies the shortening velocity of muscle, to match loading conditions without any control system. This unique variable gearing mechanism, which characterized by Architecture Gear Ratio (AGR), is involves complex interaction among three key elements: muscle fibers, connective tissue, and the pennation angle. However, how three elements determine the AGR of muscle-like actuator is still unknown. This study introduces a Himisk actuator that arranges five contractile units at a certain pennation angle in a flexible matrix, the experiment and simulation results demonstrated that the proposed actuator could vary AGR automatically in response to variable loading conditions. Based on this actuator, we present a series of actuators by simulations with the varying pennation angle (P), elastic modulus of the flexible matrix (E), and number of contractile units (N) to analyze their effects on AGR, and their interaction by three-factor analysis of variance. The results demonstrated that P and N effect on the AGR significantly, while E effects on AGR slightly, which supported the idea that the P is the essential factor for the AGR, and N is also an important factor due to the capability of force generation. This provides a better understanding of mechanical behavior and an effective optimizing strategy to muscle-like soft actuator.

Keywords Bioinspired · Actuator · Pennate muscle · Gearing mechanism

1 Introduction

Skeletal muscle has been deemed a “typical soft actuator” due to their deformable characteristics [1]. In pennate muscle, the muscle fibers are oriented at an angle relative to the muscle's line of action and rotation during contraction [2]. The rotation of muscle fibers increases the whole muscle shortening. The displacement or velocity amplification of fiber shortening can be characterized by the muscle's Architectural Gear Ratio (AGR), which is defined as the ratio of

muscle shortening (or muscle velocity) to fiber shortening (or fiber velocity) [3]. The range of AGR depends on the load conditions. When contracting against light loads, the pennate angle of muscle fibers undergo significant changes. Conversely, when contracting against heavy loads, muscle fibers rotate less and muscle thickness and displacement decreases, which indicates that pennate muscles act as a “automatic transmission system” which is an important mechanical feature of skeletal muscle.

In recent years, a variety of soft actuators have been developed with the aim to replicate mechanical features; for example, dielectric elastomers [4–7], shape-memory alloys [8–10], fiber-based and polymer carbon artificial muscles [11–13], and fluidic actuators [14–20]. All artificial actuators demonstrated here can achieve linear contraction, high strain/stress, and intrinsic mechanical properties. However, to date, there are few studies that provide insight into the variable gearing property. Of these, McKibben artificial muscles [21, 22] is a most prevalent fluidic actuator, because they can expand radially when they shorten. This change is a critical feature of the variable gearing mechanism of

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soft actuators. Therefore, lots of researchers have designed skeletal muscle-like actuators based on McKibben artificial muscles. For example, Azizi et al. [14] created a pneumatic actuator by paralleling five McKibben artificial muscles in an array. Similar to skeletal muscle, the pennate array of McKibben is well demonstrated to be a load-dependent variable gearing mechanism. However, this design lacks the complex architectural features, such as the connective tissue, which will alter the deformation mechanism of actuator, thus to influence the gear ratio. There is still a significant gap between artificial muscle and biological skeletal muscle. The interaction of contractile units, pennation angle, and flexible behavior of connective tissue remains unknown. Roche et al. [15, 18] reported a pneumatic artificial heart by embedding contractile units into a flexible matrix to achieve a heart-like rotational motion. Actuation of the myocardium is different from skeletal muscle but provides a valuable reference for the design of skeletal muscle, as natural muscle actuation can be achieved by arranging muscle fibers parallel within the connective tissue [2, 3, 23].

Here, we introduced a Himisk actuator that arranged McKibben-based contractile units (MFU) in a flexible matrix with a pennation angle. MFU acts as a muscle fiber that produces an active force, and a flexible matrix acts as connective tissue that produced passive deformation due to its elastic behavior. To investigate how the MFU and flexible matrix effect on the variable gearing performance of actuator, we proposed three soft actuators (PA30-Matrix, PA30-NoMatrix, and PA0-Matrix). The results demonstrate that actuators can vary the muscle shape, pennation angle and AGR automatically in response to variable loading conditions, similar to skeletal muscle [2], and the output work (power) of the pennate actuator can be amplified, when $AGR > 1$. Based on the PA30-Matrix actuators, to evaluate how the pennation angle (P), elastic modulus of the flexible matrix (E), and number of muscle fibers (N) effect on AGR, we performed a series of actuators using variable P , E , and N based on simulation and performed three-factor analysis of variance (ANOVA). The results demonstrate that the P and N effect on AGR significantly, while the E had a negligible effect. The results supported the idea that the P is the most important factor for the variable gearing mechanism, while N is also important due to its capability of force generation [24, 25]. This provides a better understanding of mechanical behavior and an effective optimizing strategy to muscle-like soft actuator.

2 Bio-inspired Design

Skeletal muscles are composed of muscle fibers and connective tissue. The fibers are oriented at an angle relative to the muscle's line of action (Fig. 1a). When muscle fibers

are activated, they shorten in length and increase in diameters; these changes must be accommodated by increase in one or more orthogonal direction (thickness, width, or both directions). This will cause muscle contraction due to its constant volume. There is a complex interaction between muscle fiber and connective tissue during contraction [23, 26]. As depicted in Fig. 1b, the muscle fibers are oriented at an angle relative to the line of force and becoming more oblique as they shorten. The rotation of fibers increases the muscle shortening. The advantage can be characterized as the AGR, quantified as muscle shortening (or muscle velocity)/fiber shortening (or fiber velocity). The muscle operates in a high AGR, pennation angle, displacement and thickness, during rapid contractions. And with a low AGR, pennation angle, displacement and thickness, during forceful contractions. The muscle fiber force, pennate angle, and behaviours of connective tissue are the main factors affecting muscle deformation and AGR [27].

Inspired by pennate muscle, we developed three soft actuators, named PA30-Matrix, PA0-Matrix, and PA30-NoMatrix. As shown in Fig. 1c, these include 0° and 30° pennation angle arrangements with a flexible matrix, and a 30° pennation angle configuration without the matrix fabricated by pouring. The physical model of three type soft actuators is shown in Fig. 1d. This allows us to investigate the effect of MFUs and flexible matrix on the actuator's performance.

3 Methods

3.1 Numerical Simulation Methods

The simulations were performed using ABAQUS 2019 (Simulia, USA)/Standard. We used a fluid cavity interaction property and rebar layers to model the motion of MFU. The model of MFUs and flexible matrix were assumed to be isotropic with linear elastic material properties. The contractile units (Young's modulus 1.5 MPa, Poisson's ratio 0.31) [18], double symmetrical rebar layers (Young's modulus 100 MPa, Poisson's ratio 0.3) [28] with linear elastic material, and the flexible matrix with Young's modulus of 0.6 MPa and Poisson's ratio of 0.475 [28]. The interaction between the contractile units and the flexible matrix was defined as a tie constraint; the inflation behavior of the contractile units was simulated with a fluid cavity; and the applied pressure was the same as that of the pressure during the experiment. For the PA0-Matrix actuator, the MFUs and the flexible matrix were meshed using a total number of 1208 and 16,277, respectively. For PA30-NoMatrix, the MFUs and the two fix-sides were meshed using a total number of 1870 and 8158, respectively. For PA30-Matrix, the MFUs and the flexible matrix were meshed using a total number of 1183 and 14,700 quadratic tetrahedral (C3D10)

Fig. 1 Structure of the skeletal muscle and soft actuator. **a** Contraction of a unipennate muscle and the architectural gear ratio measured. **b** Muscle as a composite, hierarchical structure [23]. **c** Soft actuators of PA30-Matrix, PA30-NoMatrix, and PA0-Matrix

elements, respectively. All of the mesh for three actuators were determined through a convergence analysis by gradually increasing the mesh density until the deviations in the estimated displacement reached within 5%. The deformations, stress, and strain distributions at the maximum pressure of 0.2 MPa were simulated.

Based on the PA30-Matrix actuator's configuration and parameter ($P=30^\circ$, $N=5$, $E=0.6$ MPa), we analyzed the variable gearing mechanism with variable P , E , and N under different loads, as shown in Table 1. To further analyze the interaction of E (0.5, 0.6, 0.7, and 0.8 MPa), P (25° , 30° , 35° , 40°) and N (3, 4, 5, 6) and their effect on AGR, we

Table 1 AGR, ΔL_{muscle} , ΔL_{mfu} at different P , N , and E under different loads

AGR, ΔL_{muscle} , ΔL_{mfu}		
$P=30^\circ$, $N=5$	$N=5$, $E=0.6$ MPa	$P=30^\circ$, $E=0.6$ MPa
$E=0.5, 0.6, 0.7$ MPa	$P=25^\circ, 30^\circ, 35^\circ, 40^\circ$	$N=3, 4, 5, 6$

performed 64 sets of numerical simulations under zero load at 0.2 MPa, as shown in Table 2. (P_{25} , P_{30} , P_{35} , P_{40} represent $P=25^\circ$, $P=30^\circ$, $P=35^\circ$, $P=40^\circ$; N_3 , N_4 , N_5 , N_6 represent

Table 2 AGR at different P , N , and E under zero load at 0.2 MPa

	P_{25}	P_{30}	P_{35}	P_{40}	P_{25}	P_{30}	P_{35}	P_{40}	P_{25}	P_{30}	P_{35}	P_{40}	P_{25}	P_{30}	P_{35}	P_{40}
E (MPa)	N_3				N_4				N_5				N_6			
E_{05}	1.89	1.48	1.32	1.22	1.65	1.39	1.25	1.16	1.45	1.35	1.31	1.13	1.66	1.37	1.23	1.15
E_{06}	1.92	1.48	1.33	1.23	1.64	1.39	1.25	1.16	1.45	1.34	1.30	1.10	1.65	1.36	1.22	1.14
E_{07}	1.94	1.48	1.33	1.23	1.63	1.39	1.25	1.16	1.45	1.33	1.30	1.11	1.65	1.36	1.22	1.13
E_{08}	1.96	1.48	1.33	1.23	1.62	1.39	1.25	1.15	1.48	1.36	1.31	1.11	1.64	1.36	1.21	1.12

$N=3, N=4, N=5, N=6$; $E_{05}, E_{06}, E_{07}, E_{08}$ represent $E=0.5, E=0.6, E=0.7, E=0.8$.

3.1.1 Measures of Displacement, Pennation Angle, and Thickness

As shown in Fig. 2a, we set the middle point (point 1, point 3), and the vertex point (point 2) before the simulation to quantify the changes of displacement, pennation angle, and thickness of the PA30-Matrix actuator. The displacement of actuator was defined as a vertical contraction of soft actuator. The thickness was determined by measuring the distance between the leftmost and rightmost vertex of the actuator. The acute angle between the two adjacent edges of the actuator was measured as the pennate angle (θ). We measured the angle by linking point 1, point 2, and point 3 when actuator in stable. The measurement of displacement, pennation angle, and thickness of the PA30-NoMatrix actuator was similar to those of the PA30-Matrix actuator. However, there was a small difference at the pennation angle measurement due to it lacking a flexible matrix for reference. We obtained the angle (θ') at three points, of which point 2 was the intersection of the left edge and centerline of the

contractile unit, while points 1 and 3 was on the left edge and centerline respectively, as shown in Fig. 2b. The measurement of PA0-Matrix is shown in Fig. 2c. The PA30-Matrix, PA30-NoMatrix and PA0-Matrix actuators were tested in experiment, as shown in Fig. 3. An S-type force sensor was used to measure the actuator force, and a laser displacement sensor was used to record the displacement. The force data were collected by a DYB-5 dynamic strain gauge, and then transmit to VIBSYS vibration signal acquisition and analysis equipment. To obtain the changes of pennation angle and thickness, a digital camera was used to record the actuator behaviour. We selected two key frames corresponding to the instant before the load off the surface and also the instant when the contraction reached to stable. The two images were measured for the thickness and pennation angle.

3.1.2 Measures of AGR

The AGR of the pennate muscle was calculated as the ratio of whole muscle shortening to fiber shortening [3], or the muscle velocity to the fiber velocity during isotonic contraction [2]. We defined the AGR as the ration of actuator longitudinal shortening ($\Delta L_{\text{actuator}}$) to contractile unit

Fig. 2 Measurement of displacement, thickness, and pennation of **a** PA30-Matrix, **b** PA30-NoMatrix, and **c** PA0-Matrix actuators

Fig. 3 Experimental installation for measurement of actuator

shortening (ΔL_{mfu}) based on the standard finite element model. $\Delta L_{actuator}$ was defined as vertical displacement, and ΔL_{mfu} was the relative displacement between the two center points of the two ends of the middle contractile unit.

3.2 Data Analyses

All data analyses were performed using the IBM Statistical Package for the Social Sciences (SPSS) Statistics software version 26 (SPSS Inc., Chicago, IL, USA). Three-way ANOVA was used to test the significance of the P , N , and E for the AGR under the conditions of P at 25°, 30°, 35°, and 40°; N at 3, 4, 5, and 6; and E at 0.5 MPa, 0.6 MPa, 0.7 MPa, and 0.8 MPa, respectively. The valid numbers for the simulations analyzed are shown in Table 2. Statistical significance was set at $p < 0.05$.

4 Results

4.1 Deformation of Three Actuators

As shown in Fig. 4, the model predicted load-dependent changes of actuators during experiment (Fig. 4a) and simulation (Fig. 4b, c). The deformation of soft actuators under different loads are shown in Fig. 4b. As expected, the MFUs contracted in length and expanded in diameter when air pressure was applied, this resulted in deformation of soft actuator. Compared with the test (Fig. 4a) and simulation (Fig. 4b), three actuators show similar deformations. In addition, the displacements and thickness all decreased with the loads increasing. The stress of the three actuators was depicted in Fig. 4c. When at low-loads, the increased penetration angle and small passive stretch of the flexible matrix

Fig. 4 Finite element simulations of the PA0-Matrix, PA30-Matrix, and PA30-NoMatrix actuators with varying application loads. **a** The recorded deformations of actuators when acting against the increased

load (0, 5, 16, and 27 N) at an air pressure of 0.2 MPa. **b** Vertical displacement. **c** von Mises stress

tended to increase the actuator thickness and displacement. At high-load contraction, the decreased pennation angle and large passive stretch of the flexible matrix decreased thickness and displacement. There are notably tensile deformations present in the PA30-Matrix and PA0-Matrix actuators at the position where the loads were applied. The PA30-NoMatrix actuator has no obvious tensile deformations due to the rigid connecting. The results demonstrated that the finite element model can clearly reveal the deformation and driving mechanism of the soft actuator.

To further verify the deformation of three actuators, we quantified the displacement, pennation angle, and thickness as shown in Fig. 5. Large displacement of actuators was generated at low loads, and small displacements were generated at high loads (Fig. 5a–c). The predicted pennation angle (Fig. 5d–f) and thickness (Fig. 5g–i) decreased as the loads increased as well. Load-dependent variation of changes in thickness and pennation angle resulted in a load-dependent AGR. The AGR decreased significantly as the load increasing, which the trend is similar to the biological muscle and the experiment (Fig. 5j, k). However, there were disagreements between the Finite Element Analysis (FEA) and the

experiment for PA30-Matrix actuator (Fig. 5j). In simulations, deformation of the rebar layer is determined from the deformation gradient of the underlying shell. However, in experiment, when the woven mesh changed their orientation during contraction, its deformation is not only determined from the deformation of the underlying flexible tube but the frictional resistance from flexible matrix and flexible tube as well. The additional friction will limit the shortening of MFU in experiment lower than that in the simulation. In addition, the $\Delta L_{\text{actuator}}$ in simulation is lower than the experiment, the displacement of actuator at zero loads is about 14.9 mm, which is lower than the experiment (17.0 mm). In the paper, the AGR of the soft actuator was calculated as the ratio of $\Delta L_{\text{actuator}}$ to ΔL_{mfu} . For the PA30-matrix actuator, its $\Delta L_{\text{actuator}}$ in simulation is lower than the experiment. Therefore, the accumulative error contributes to the large relative error. However, the relative error was not influenced the tendency of deformation (displacement, thickness, pennation angle) and AGR, all of them decreased with increasing loads, similar to skeletal muscle. And it does not affect the judgment of the variation tendency. The AGR of the PA30-Matrix was maximum (AGR = 1.4) and had a wide speed

Fig. 5 Comparison between displacement, thickness, and pennation angle of PA30-Matrix, PA30-NoMatrix, and PA0-Matrix actuator in the experiment and simulation. **a–c** Displacement of PA30-Matrix,

PA30-NoMatrix, and PA0-Matrix actuators. **d–f** Thickness of three actuators. **g–i** Pennation angle of three actuators. **j–l** AGR of three actuators

range, this result demonstrated that the variable gearing mechanism presented in the actuator was mediated by the pennation angle and the flexible matrix material. Variable gearing system that is directly integrated to pennate MFUs in an adaptable flexible matrix, which is elegant and simple without gears or clutches compared with conventional ones.

4.2 Theoretical Model of Deformation

To verify the necessity of contractile units and flexible matrix for the gearing mechanism of HimiSK actuator, and illustrate how to achieve beneficial gearing mechanism by their deformation, a theoretical model of the pennate

Fig. 6 Theory model of HimiSK actuator

actuator motion is established, as shown in the Fig. 6. As shown in Fig. 6a, the PA30-Matrix actuator is simplified into a parallelogram model. The edge A considers fixed in the process of movement. It decomposes the motion of the contraction unit into axial contraction, radial expansion, and rotational motion. The PA0-Matrix actuator is simplified as a rectangular model (Fig. 6b), which decomposes the movement of the contraction unit into axial contraction and radial expansion.

a is the initial state of the contractile unit, and the effective length is I_1 ($I_1=96$ mm). a_1 is the stable state of contraction and rotation after the contractile unit subjected to air pressure, and its length is I_2 mm. b is the displacement of the end of the contractile unit, and length is I_3 mm, calculated by formula (1). θ is the angle between A and a ($\theta=30^\circ$), and θ_1 is the angle between a and a_1 , which is the angle (Δ Pennation) generated during the rotation of contractile unit. The angle between a and b is θ_2 , obtained by the formula (2). θ_4 is the angle between the B-side of the actuator and the vertical direction, $\theta_4=15^\circ$. The angle of θ_3 is obtained. $\theta_3=15^\circ-\theta_2$. The vertical displacement of the contraction unit is L_1 , $L_1=I_3\cos\theta_3$ mm. The horizontal displacement is T_1 . $T_1=I_3\sin\theta_3$. c is the radial expansion of the contractile unit, and its length is Δd mm. Because the contractile units in the actuator is subjected to high pressure, the interference may occur during the expansion of

each contraction unit. The deformation of the contractile unit in the expansion direction is calculated by the expansion deformation of the whole actuator. The deformation is ΔD mm. θ_5 is the angle between the c and the vertical direction. $\theta_5=75^\circ-\theta_1$. The angle varies with the pinnate angle. The vertical displacement generated during the radial expansion of the contractile unit is L_2 , $L_2=\Delta D\cos\theta_5$. A horizontal displacement T_2 is generated, $T_2=\Delta D\sin\theta_5$. The total displacement of the actuator is L , calculated by formula (3) and the thickness is T , calculate by formula (4):

$$I_3 = \sqrt{I_1^2 + I_2^2 - 2I_1I_2}, \quad (1)$$

$$\theta_2 = \arccos \frac{I_1^2 + I_3^2 - I_2^2}{2I_1I_3}, \quad (2)$$

$$L = L_1 + L_2 = I_3 \cos \theta_3 + \Delta D \cos \theta_5, \quad (3)$$

$$T = T_2 - T_1 = \Delta D \sin \theta_5 - I_3 \sin \theta_3. \quad (4)$$

There is no flexible matrix material in PA30-Nomatrix actuator. Matrix parameters are not affected in deformation. Therefore, the I_2 and ΔD of the PA30-Nomatrix actuator are measured first. The deformation blocked coefficient γ was obtained at different air pressures after adding the flexible

Table 3 The parameter of three actuator

Actuator		Pressure	0	0.04	0.08	0.12	0.16	0.20
PA30-NoMatrix	I_2		0	3.354	5.575	8.92	11.15	13.38
	ΔD		0	2.23	5.575	8.92	11.15	13.38
PA30-Matrix	I_2		0	3.258	4.887	8	10	12.069
	ΔD		0	2.166	4.887	8	10	12.069
PA0-Matrix	I_2		0	2.258	4.887	8	11	13.069
	ΔD		0	2.166	4.887	8	10	12.069

Fig. 7 Comparison of displacement and thickness of three actuators

matrix. The I_2 and ΔD of PA30-matrix and PA30-matrix actuator is obtained, as shown in Table 3.

The actuator displacement L and thickness T were compared with the experimental data, under zero load and different pressures (0, 0.04, 0.08, 0.12, 0.16, 0.20 MPa), as shown in Fig. 7. It can be seen that the displacement and thickness of the three actuators have the same trend with the experiment, and the values are in good agreement. It indicates that the movement of the soft actuator is mainly caused by the axial contraction and radial expansion of the contractile unit. It causes the flexible matrix to deform in the direction of thickness, which drives the contractile unit to rotate and benefit to the contraction of actuator.

It can be clearly seen from Fig. 7a–c that the displacement of the pennate actuator (PA30-matrix (17 mm)) is higher

than that of the parallel actuator (PA0-matrix (12 mm)). Although, the pinnate angle reduces the displacement in the vertical component of contractile unit, the displacement of whole actuator in the vertical exceeds the contractile unit, due to the shape changes of flexible matrix of PA30-matrix actuator and the contraction of contractile units. All the contractile units and flexible matrix are the necessary elements for the gearing mechanism. The flexible shape change of soft actuator is a flexible gearing system, its gearing mechanism facilitate shortening length of actuator exceed the shortening length of contractile unit itself, which makes the $AGR > 1$. Therefore, the shortening length of the actuator is amplified. Under the same load, the output work of the pennate actuator is larger than that of the non-pennate actuator when $AGR > 1$

Fig. 8 The output work of PA30-Matrix and PA0-Matrix actuators

(formula (5)), as shown in Fig. 8, Where F respective the output force:

$$W_{\text{out}} = F \cdot \Delta L_{\text{actuator}} = \text{AGR} \cdot F \cdot \Delta L_{\text{mfu}}. \quad (5)$$

4.3 AGR at Different Loads Conditions

We analyzed AGR based on the PA30-Matrix actuators, which with the optimal AGR. When $P = 30^\circ$ and $N = 5$, the E was variable. When $N = 5$ and $E = 0.6$ MPa, the P was variable. When $E = 0.6$ MPa and $P = 30^\circ$, the N was variable. As shown in Fig. 9, during nearly all contractions, the shortening of the actuator decreased noticeably as the load increasing (Fig. 9a, d, g), which was similar to the skeletal muscle. In addition, the shortening of MFUs did not particularly change with loads (Fig. 9b, e, h), which is consistent with the McKibben pneumatic muscle [21, 22]. The contraction of the whole actuator exceeded the contraction of the MFU for all actuators, when $\text{AGR} > 1$. The calculated AGR significantly decreasing as the load increased at different levels of P , E , and N (Fig. 9c, f, i, respectively). This variable gearing mechanism was similar to a phenomenon that has been observed in pennate muscles [14]. The results demonstrate that the dynamic actuator-shape changes promote MFU rotation at low forces and resist MFU rotation at high forces. Therefore, actuator-shape changes act as an automatic transmission system, which can work from a high gear during rapid contractions to a low gear during forceful contractions without the sensory information or feedback control. In addition, the variable gearing mechanism was

influenced by the parameter of P , N , and E . The E effect on AGR is slight but effect on $\Delta L_{\text{actuator}}$ significantly. The analysis provides a better understanding of mechanical behavior of muscle-like soft actuator.

4.4 AGR with Variable E , P , and N at Zero Load

Further evaluation of the interaction of P (25° , 30° , 35° , and 40°); N (3, 4, 5, and 6); and E (0.5 MPa, 0.6 MPa, 0.7 MPa, and 0.8 MPa), and their influence on AGR was carried out. The 64 sets of simulations are performed under zero load at 0.2 MPa (Fig. 10). Figure 10a–d show the $\Delta L_{\text{actuator}}$ at different N , P , and E . The $\Delta L_{\text{actuator}}$ increased with the P , E decreased, and N increased. When the actuator with a low P and E , the MFUs can rotate to a great angle, thus to generate a larger displacement. In addition, since the MFU was the main element of force generation, a larger N could produce a larger displacement as well. In the case of N at 6 and E at 0.5 MPa, the displacement was lower, due to a small deformation space between the adjacent contractile units. Figure 10e–h reveal the shortening of the contractile unit (ΔL_{mfu}). The ΔL_{mfu} increased with P , N increased, and E decreasing. Figure 10i–l shows the impact of P on the AGR was greatest (from 1.2 to 1.9, Fig. 10i), and the curves of AGR at different E was similar, because the shortening of contractile units and the actuator were relatively close in the same materials. The results supported the idea that P is the most important factor for the variable gearing mechanism, which is similar to pennate muscle. And the contractile unit was an important factor for variable gearing mechanism as well, due to its capability of force generation. E is a decisive factor affecting displacement/velocity of the actuator but had a negligible influence on the AGR, because the shortening of contractile units and the actuator were relatively close in the same materials. This will provide an effective optimizing strategy for muscle-like soft actuator.

5 Discussion

5.1 Analysis of the Main and Interaction Effects

To further inspect which factor (P , E , or N) was most significant on AGR, three-way ANOVA was performed. The main effects and their interaction effects were illustrated terms of the F value, p value ($p < 0.05$), and partial η^2 value, as shown in Table 4. The analysis results showed that (1) two main effects were significant for AGR: the main effect of P and N ($p < 0.001$). The main effect of P can be interpreted as the average difference between the four P groups (25° , 30° , 35° , and 40°) across different subgroups (i.e., N and

Fig. 9 Changes in actuator, contractile unit displacement, and AGR of loads. **a–c** Changes in actuator displacement, contractile unit displacement, and AGR when E is variable. **d–f** Changes in the N variable. **g–i** Changes in the P variable

E). The main effect of N can be interpreted as the average difference between four N groups (3, 4, 5, and 6) across different subgroups (i.e., P and E). (2) The main effect of E ($p=0.323$) and the interaction effect of P and E ($p=0.544$) were not significant. (3) Two interaction effects were significant for AGR: the interaction effect of P and N ($p<0.001$) and the interaction effect of E and N ($p=0.034$). The interaction effect of P and N can be interpreted as the difference between four P groups in different N groups. The interaction effect of E and N indicated that there was a significant N effect, and the N effect depended on the condition of the E group. The results suggest that the $P \times N$ and $N \times E$ effects should be investigated in single effect analysis for detailed interpretations.

5.2 Analysis of the Single Effect and a Comparison

As shown in Tables 5 and 6, the single effect analysis revealed significant differences between the interaction of N and P , E and N , respectively. Table 5 shows the F value, p value, and partial η^2 of the AGR for the interaction of N and P . There was a significant difference ($p<0.001$) between the single effect of P and N . Table 6 shows the F value, p value, and partial η^2 of the AGR for the interaction of N and E . There was a significant difference ($p<0.001$) in the single effect of N ; but there was no significant difference ($p>0.05$) in the single effect of E , except for in the case of $N=4$ ($p=0.02$). Partial η^2 in Tables 5 and 6 demonstrate that

Fig. 10 Changes in AGR of loads at zero loads. **a–d** Changes in actuator displacement. **e–h** Changes in contractile unit displacement. **i–l** Changes in AGR

Table 4 *F* value, *p* value and partial η^2 value with consideration for the interaction

	<i>F</i>	<i>p</i>	Partial η^2
<i>N</i>	4644.64	<0.001	0.984
<i>P</i>	31,969.635	<0.001	0.998
<i>E</i>	15.918	0.323	0.119
<i>N</i> × <i>P</i>	502.316	<0.001	0.952
<i>P</i> × <i>E</i>	4.621	0.544	0.230
<i>N</i> × <i>E</i>	9.219	0.034	0.451

the effect of *P* on AGR was higher than that of other factors (*E* and *N*), which was similar to the phenomenon that occurs in pennate muscle, in which the pennation angle is the main factor in the variable gearing mechanism. *N* also influences the AGR due to muscle fiber with the capability of force generation. *E* has a negligible influence on the AGR.

6 Conclusion

In this paper, we presented three types of actuators by varying the arrangement of contractile units and the flexible matrix, termed PA30-Matrix, PA30-NoMatrix, and

PA0-Matrix, respectively. We have demonstrated that all the actuators present load-dependent variable gearing mechanism, and PA30-Matrix actuator with the wide range of AGR. Based on the PA30-Matrix actuator, a series of simulations were performed with a variable pennation angle (*P*), modulus of elasticity (*E*), and number of contractile units (*N*) to investigate their interaction and effects on the variable gearing mechanism. Our study results demonstrated that the *P* and *N* significantly affect AGR ($p < 0.001$), individually and in combination ($P \times N$ and $N \times P$), *E* has negligible influence on the AGR ($p > 0.05$). The results supported the idea that *P* is the most important factor for the variable gearing mechanism, which is similar to pennate muscle. The contractile unit was an important factor variable gearing mechanism as well, due to its capability of force generation. *E* is a decisive factor affecting displacement/velocity of the actuator. The analysis of primary parameters and their interaction for the load-dependent variable gearing mechanism will provide a better understanding of mechanical behavior and an effective optimizing strategy for muscle-like soft actuator.

Table 5 *F* value, *p* value, and partial η^2 value with consideration for the single effect analysis between *N* and *P*

<i>N</i>	<i>P</i>	<i>F</i>	<i>p</i>	Partial η^2	<i>P</i>	<i>N</i>	<i>F</i>	<i>p</i>	Partial η^2
3	25, 30, 35, 40	2009.837	<0.001	0.996	25	3, 4, 5, 6	517.489	<0.001	0.983
4	25, 30, 35, 40	868.719	<0.001	0.990	30	3, 4, 5, 6	86.035	<0.001	0.905
5	25, 30, 35, 40	852.684	<0.001	0.990	35	3, 4, 5, 6	71.990	<0.001	0.889
6	25, 30, 35, 40	1073.572	<0.001	0.992	40	3, 4, 5, 6	49.957	<0.001	0.847

Table 6 *F* value, *p* value, and partial η^2 value with consideration for the single effect analysis between *E* and *N*

<i>E</i>	<i>N</i>	<i>F</i>	<i>p</i>	Partial η^2	<i>N</i>	<i>E</i>	<i>F</i>	<i>p</i>	Partial η^2
0.5	3, 4, 5, 6	103.575	<0.001	0.920	3	0.5, 0.6, 0.7, 0.8	2.140	0.119	0.192
0.6	3, 4, 5, 6	131.679	<0.001	0.936	4	0.5, 0.6, 0.7, 0.8	3.852	0.020	0.300
0.7	3, 4, 5, 6	149.408	<0.001	0.943	5	0.5, 0.6, 0.7, 0.8	1.293	0.297	0.126
0.8	3, 4, 5, 6	168.735	<0.001	0.949	6	0.5, 0.6, 0.7, 0.8	1.328	0.286	0.129

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Declarations

Conflict of interest The authors declare that there is no conflict of interest.

Ethical approval This article does not contain any studies with human or animal subjects performed by any of the authors.

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