# A Preliminary Study on the Application of Linear Electric Motors to Upper Limb Prostheses

**Aline Durrer Patelli Juliani**[1]
orcid.org/0000-0002-1335-8429

**Diógenes Pereira Gonzaga**[2]
orcid.org/0000-0002-7736-780X

**Diego Santos Greff**[3]
orcid.org/0000-0002-0596-6790

**Alexandro Garro Brito**[4]
orcid.org/0000-0003-1160-7476

[1]Department of Mobility Engineering, Federal University of Santa Catarina, Joinville, Santa Catarina, Brazil.
E-mail: aline.juliani@ufsc.br

[2]Retired Professor from Department of Electrical Engineering, São Paulo University, São Carlos, São Paulo, Brazil.
E-mail: dioper@terra.com.br

[3]Department of Mobility Engineering, Federal University of Santa Catarina, Joinville, Santa Catarina, Brazil.
E-mail: diego.greff@ufsc.br

[4]Department of Mobility Engineering, Federal University of Santa Catarina, Joinville, Santa Catarina, Brazil.
E-mail: alexandro.brito@ufsc.br

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## ABSTRACT

Current human artificial prosthesis technology relies on rotational motors driving geared mechanisms. However, using electric rotational motors with planetary gears and lead screw transmissions to convert rotational movement into linear motion presents several challenges. Key issues with applying rotational motors in prostheses include mechanical complexity and operational noise. A driving system based on linear electric motors could offer a simpler mechanism, as the motor is designed to generate linear motion directly without additional mechanical components. This approach can be advantageous in terms of operational simplicity and reduced noise.

This paper presents a preliminary study on the application of linear electric motors in upper-limb prostheses. It outlines the technology behind linear electric motors, comparing their advantages and disadvantages to those of rotational motors. Focusing on the prosthesis problem, the study proposes a configuration for linear electric drive systems. Additionally, a preliminary laboratory setup for benchmarking is presented, aiming to test and validate the motor design based on the expected specifications for upper limb kinematic movement.

While the prototype is not yet fully compatible for real-world use, it serves as a conceptual simulator, providing valuable insights for prosthesis development. The results demonstrate that linear motors can be effectively used to drive artificial prostheses, delivering the necessary force and speed for a practical application. Based on these findings, further research is needed to develop an upper-limb prosthesis that meets usability requirements, incorporating appropriate materials and components.

**KEY-WORDS:** Actuators; Artificial hand; Hand prostheses; Linear motors; Tubular linear synchronous motors; Upper limb prostheses;

# 1 INTRODUCTION

Electric motors are used in different applications and environments since they are essential to the daily use of human beings. The latest technological advances in electric machines have resulted mainly from power semiconductors and materials developments. These advances directly interfere in areas with specific features in the actuator design, like bioengineering. Some improvements are consequences of the electric motor drive advances, efficiency increase, and motor size and volume reductions. The customized electric motor design can meet specific characteristics and priorities. This approach could be helpful in artificial hand projects that use this component as an actuator.

The needs of upper limb prosthesis users are cited by Cordella *et al.* **[1]**. The motor design could directly or indirectly attend to these demands, such as the reliability of the battery, the ability to perform activities with higher strength, improvement of heat dissipation, and reduction of the noise (caused by mechanical adaptations).

The replacement of human hands by prostheses has the challenge of accommodating the actuators, sensors, and electronic components. This task should maintain the same size and weight as the natural organ **[1]**. Besides, the artificial hand should be functional, affordable, durable, and cosmetic **[2]**.

Usually, researchers and publications about upper limb prostheses show biomechatronic designs **[3-4]**. Some other works present control strategies, mainly to obtain, record, and recognize patterns of myoelectric signals **[5]**. Other papers develop sensory feedback **[6]**. Specific discussions about the electric motor selection and its features are rare. In addition, detailed mechanical adaptations (gearbox and leadscrew) together with the motor are rarely mentioned.

Frequently, the concept of a linear actuator is confused with the terminology of the linear motor in the biomedical literature. In many works, such as **[7-11]**, rotational electric motors with some mechanical devices provide linear motion, referred to as linear motoring. However, linear motors are conceptually designed to produce linear motion without requiring additional mechanical components to convert rotational movement into linear movement.

A common disadvantage of geared motion is the noise generated by the operation of mechanical components. Additionally, noise is another significant concern in biomechanical devices.

Especially for hand prostheses, the high sound produced by the mechanisms (rotational motor with planetary gears and lead screw transmission) is inconvenient. It can even be the cause of disrupting social interactions **[1, 3, 12]**. A prosthesis with fewer mechanical devices can be adequate in this context. Hence, the movement drive from a linear electrical machine, with a smaller quantity of additional components, becomes an attractive alternative for human prostheses.

This paper proposes a preliminary study of the conceptual application of linear motors to drive finger prostheses. It presents the basic concepts of linear electric motors, like constructive and operation characteristics, advantages, and disadvantages. This work also discusses the steps of the motor design procedure. A conceptual prototype was made to validate theoretical calculations. This stage of development does not aim to create a final prosthesis for application in a human hand. It focuses on establishing a benchmarking laboratory environment to test the driving concept for verifying the kinematic aspects, strength demands, operational noise, and comparisons according to the upper limb prosthesis application. It is noteworthy to mention that the presentation of a final human prosthesis, with proper dimensions and operation, is not the objective at this stage of development, but the conceptual study of linear electric motor applied to the upper limb prosthesis.

Experimental measurements achieved machine parameters and force similar to the theoretical design. Preliminary tests on a prosthesis prototype also demonstrate the linear motor ability to provide the proposed finger actions. A noise level reduction was obtained as well. Hence, these results motivate the application of the linear motor instead of the rotational motor (and mechanical adaptations) to obtain silent linear movement. Consequently, this replacement reduces the number of components and maintenance. Linear motor use in biomedical applications is promising, and it can solve some technical problems faced by previous studies.

This work is organized as follows. The concepts of linear electric motors and basic information about upper limb prostheses are presented in sections 2 and 3. The motor design and prototype are in section 4. Finally, the results and conclusions are discussed in sections 5 and 6.

## 2 CONCEPTS OF ELECTRIC LINEAR MOTORS

A rotational motor cut and unrolled along its longitudinal axis transforms it into a linear motor **[13]**. The static part is denoted as a stator, while the mobile part is known as a linor.

According to their constructive characteristics, there are three types of linear machines: 1) Plane Motors: this is the most common type, where there is a movable plane (linor) over the static plane (stator), shown in Figure 1a; 2) Sectorial Motors: the stator is different from the rotational motors. It does not involve the mobile part. Therefore, the stator has a bump (Figure 1b); 3) Tubular Motors: are derived from the plane motors, with a circular (Figure 1c), square, or rectangular cross-sectional view. In this case, the internal linor moves along the longitudinal axis.

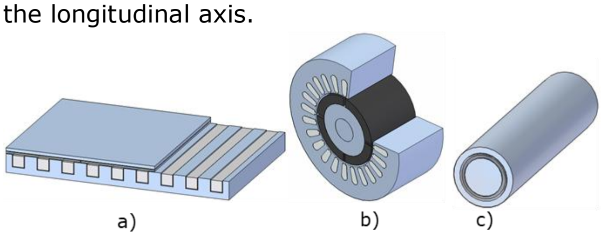


**Figure 1** – Types of linear motors.
**Source:** authors.

### 2.1 Operational characteristics of Linear Motors

The classification of the most common linear motors is made by the operation and topology, like direct current, induction, and synchronous motors. These machines have different operations, but the physical principle that produces the electromagnetic force is the same. The magnetic fluxes created by the stator and the linor generate the force that moves the linor.

#### 2.1.1 Direct Current (DC)

DC motor stators produce a static magnetic field through permanent magnets or windings. The linor produces another adjustable field through a controlled direct voltage. Both fields (from the stator and the linor) should switch their interactive field vector during the linor movement to produce the linear force by a commutator-brush mechanism **[14]**. This device is severely inconvenient because it produces operational sparks, which damage the carbon brush, demanding regular maintenance. Moreover, DC motors have lower efficiency when compared to other technologies. Hence, the linear DC motor arouses little interest in the practice **[13]**.

#### 2.1.2 Induction

Windings inside a ferromagnetic or non-ferromagnetic material constitute the stator. Usually, the linor consists of a conductive sheet on a solid iron. To these characteristics, AC currents supply the coils in the stator, producing a traveling field in the airgap, which induces a voltage in the linor **[14]**. The interaction between the created fluxes generates the force.

Industries and transportation systems commonly use linear induction motors (LIMs). According to Boldea *et al.* **[15]**, studies have provided good energy conversion efficiency (above 80%). However, the power factor remains low due to mechanical constraints.

In addition to the mentioned characteristics, the LIMs have a complex electric control for low speeds.

#### 2.1.3 Synchronous

The currents in the windings and the permanent magnets create the magnetic fields. The interaction of the magnetic fields generates the force. The supply could be AC or DC voltage with an electronic converter.

The term brushless means the absence of brushes and mechanical commutators due to the permanent magnet synchronous machine, with a non-sinusoidal magnetic flux density waveform at the airgap (brushless DC) operating with the power converter. This group behaves like a DC machine but with an electronic commutator **[16]**.

The brushless AC implies sinusoidal excitation, and the ideal back-EMF has a waveform equal to the supply. The motor and the electric control are physically similar to the brushless DC. Some specific brushless machine types are the stepping and the switched reluctance motors.

Stepping motors have windings in the stator. Permanent magnets or ferromagnetic material (variable reluctance) constitute the linor. They do not require position sensors. Positioning systems that demand high precision and rapid acceleration are examples of applications **[16]**.

The stepping motors have an unfavorable feature of mechanical resonance at a low speed **[17]**. It causes oscillations and a reduction of the electromagnetic force. Due to this characteristic, this machine type is not suitable for upper limb prosthesis applications.

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Switched reluctance motors have a topology similar to the stepper motors. The current switching requires a position sensor. The force is very sensitive to these transitions **[16]**.

## 2.2 End Effects

The main disadvantages of linear motors over rotational motors are the end effects.

The end effect is known as the magnetic flux leakage at the physical boundaries of the machine. Such leakage reduces the magnitude of electromagnetic force and the motor efficiency. In a rotational motor, the end effect is smaller than in a linear due to the machine's physical structure. As it is a closed magnetic circuit, the magnetic flux in the airgap is well concentrated inside the machine, so the end effects are negligible.

The linear motor is an open magnetic circuit. In a plane motor, there are leakage magnetic fluxes at the longitudinal ends during the operation. Moreover, a transversal leakage occurs when the linor width is larger than the stator width. Both effects decrease the electromagnetic force magnitude and the machine's efficiency.

## 2.3 Comparisons among the Main Linear Motors

Upper limb prosthesis requires motor selection through the fundamental characteristic analyses of each electric machine.

The DC motors have lower force density, efficiency, and reliability than the induction and synchronous machines. Furthermore, they require periodic maintenance due to the presence of brushes.

The induction motors demand fewer maintenance actions and more complex electrical control at low speeds than the brushless synchronous motors. Because of this, brushless motors are the best option for modern biomedical applications.

Generally, the brushless DC motor has magnets on the surface (radial magnetization), and the AC machine has magnets on the interior (axial magnetization). The first one is simpler than the second, considering constructive aspects. Bianchi *et al.* **[18]** compare tubular linear motors with magnets on the surface (TL-SPM) and in the interior (TL-IPM). TL-SPM has a slightly lower force and lower ripple force than TL-IPM. This feature is relevant to an application that needs few oscillations in the force waveform.

Therefore, the tubular permanent magnet synchronous machine, specifically brushless DC, is the best option for upper limb prosthesis.

## 2.4 Comparisons Between Linear and Rotational Motors to Provide Linear Motion

Boldea **[14]** makes comparisons between linear and rotational motors, with mechanical adaptations, to provide linear motion in industrial usage. Some advantages of the linear motors for speed control performance are higher linear speeds, faster acceleration, high reliability for long life due to simplicity, low maintenance costs, and high repeatability.

# 3 UPPER LIMB PROSTHESES

Prostheses can substitute an absent limb of the body and improve the life quality of patients. An ideal prosthesis should have the same motor capacities and be similar to the limb of the human body that it replaces. However, this concept has been improved over the years but is still not a reality.

According to Carrozza *et al.* **[3]**, increasing the degrees of freedom (DOF) should solve the limited capacity of grasp and non-natural movement during grasping. Adaptation or development of mechanisms, sensors, actuators, and controls can increase the DOF. In addition, some restrictions need attention, such as energetic consumption, appearance, size, mass, and loudness.

The transmission mechanisms are mechanical components that move the prosthesis. They can be directly connected to the motor shaft or via a cable. The second type of connection is more similar to the human tendon than the first. In the future, electric motors connected with cable transmissions will remain important because of the high force required and a desire for a limited profile **[19]**.

In this work, the demands of the electric motor are according to the soft gripper mechanism. It was developed by Hirose and Umatani **[20]** and adapted by Zollo *et al*. **[8]**. This mechanism needs a single linear actuator (Figure 2) to move a finger (with 3 DOF). Pulleys represent the joints, springs are responsible for the extension movement, and a cable is connected to the actuator to perform the flexion. These components constitute the artificial index finger.

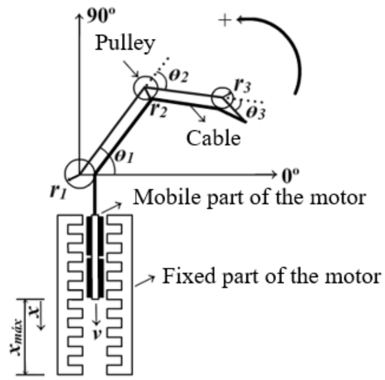


**Figure 2 –** Schematic representation of the index finger connected to the linear motor.
**Source:** authors.

It is necessary to determine the maximum displacement of the mobile part of the actuator ($x_{max}$ in Figure 2) to move the artificial finger. This is necessary to design the motor.

The linear displacement, $x$ (m), was equated by Zollo *et al.* **[8]** and presented by (1).

$$x = r_1 \cdot (\theta_1 - \theta_{10}) + r_2 \cdot (\theta_2 - \theta_{20}) + r_3 \cdot (\theta_3 - \theta_{30}) \quad (1)$$

Where:
$\theta_1$, $\theta_2$, and $\theta_3$ are the angular positions for each joint (rad);
$\theta_{10}$, $\theta_{20}$, and $\theta_{30}$ are the initial angular positions for each joint (rad);
$r_1$, $r_2$, and $r_3$ are the pulley radii (m).

Human movements can be mimicked and expressed by kinematic functions, considering the coupling among the finger joints **[21]**. Firstly, a sequence of images of some movement is acquired. Then, a kinematic function is expressed based on digital image processing techniques. Cunha *et al.* **[21]** equated the angular positions for joints of the index finger to realize the tridigital pinch.

To understand the required linear displacements of the motor to execute other hand-typical movements, they were calculated based on the kinematic functions available in Cunha **[22]**. The maximum linear displacement values were 0.9 cm to execute the hook grip and 1.91 cm to perform the pinch grip. These maximum values were used as the initial requirement to design the first motor version.

## 4 MOTOR PROTOTYPE DESIGN

An anatomical hand can achieve a force up to 400 N. This value to perform the daily activities is 0-67 N **[23]**. The required force depends on the actuator, the transmission method, the hand configuration, and the object dimensions **[24]**. The motor design needs to attend to the application requirements. In this case, they are speed, force, power supply, volume, and other characteristics.

According to Carrozza *et al.* **[3]** and Zollo *et al.* **[8]**, the linear motor applied to a hand prosthesis should have the force and speed indicated in Table 1. Section 3 shows the required displacement of the linor. The maximum length and diameter, determined by the male forearm **[25]**, are shown too.

**Table 1 –** Linear motor characteristics determined as target to design.

| Characteristics | Values |
|---|---|
| Maximum speed (m/s) | 0.02 |
| Displacement of the linor (cm) | 1.91 |
| Nominal Force (N) | 12 |
| Maximum length (cm) | 25 |
| Maximum diameter (cm) | 3 |
| Mass (Kg) | As small as possible |
| Power supply (V) | As small as possible |

**Source:** Carrozza *et al.* **[3]**, Zollo *et al.* **[8]** and authors.

Like rotational machines, linear permanent magnet synchronous motors have many topologies.

### 4.1 Stator and Linor

The selected stator is lengthy instead of short because of the magnetic field concentrations in the motor interior, which could interfere with the patient's ambient.

The shape is tubular with a force per mass unity higher than the plane. It has a unique face to have a constructive facility and slots to obtain higher force than the slotless configuration.

The mobile part has three configurations: magnets, windings, and moving coil **[13]**.

The linor with magnets has the lowest volume and the most simplicity compared to the other two types. These are the reasons to choose it.

### 4.2 First Estimated Configuration

The motor design optimization process depends on mathematical algorithms, where the problem needs to be precisely defined **[26]**. In this stage, a preliminary design validates that the linear machine could actuate an artificial finger. Then, the optimal dimensions of tubular motors perform the calculations instead of optimizing the complete process. Figure 3 shows the axial view of the linear motor and its sizes.

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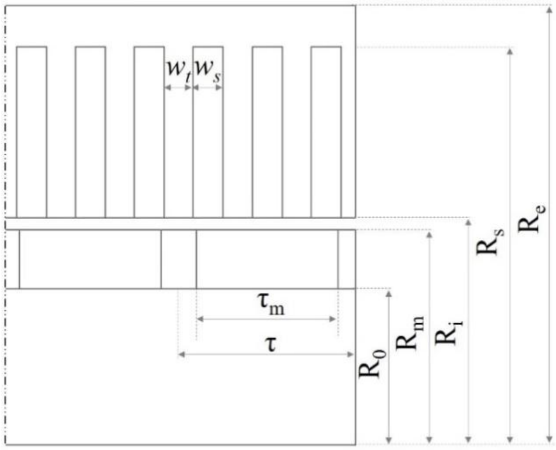



**Figure 3 –** Dimensions of the motor axial view.
**Source:** authors.

Table 2 shows the dimensions of the motor axial view.

**Table 2 -** Design Parameters of the first estimated motor.

| | | |
|---|---|---|
| $R_0$ | (cm) | 0.53 |
| $R_m$ | (cm) | 0.73 |
| $R_i$ | (cm) | 0.77 |
| $R_s$ | (cm) | 1.35 |
| $R_e$ | (cm) | 1.49 |
| $w_s$ | (cm) | 0.1 |
| $w_t$ | (cm) | 0.1 |
| $\tau$ | (cm) | 0.6 |
| $\tau_m$ | (cm) | 0.48 |
| Stator length | (cm) | 10.8 |
| Linor length | (cm) | 8.4 |
| Power supply (inverter) | (V) | 15 |
| Rated speed | (m/s) | 0.02 |
| Rated current | (A) | 0.84 |
| Resistance per phase | (Ω) | 6.12 |
| Self-inductance per phase | (mH) | 2.30 |
| Mutual inductance per phase | (mH) | 0.30 |
| Motor mass | (g) | 477 |

**Source:** authors.

Wang and Howe **[27]** show the optimal ratio ($\tau_m/\tau$) between the magnet size ($\tau_m$) and the pole pitch ($\tau$) to obtain a minimum harmonic distortion in the airgap magnetic field and force ripple. The relation ($R_m/R_e$) between the magnet radius ($R_m$) and external radius ($R_e$) represents the balance between the magnetic and electric loadings for thermal performance. This ratio has an optimal value to maximize the force density versus the relation ($\tau/R_e$).

According to the application demands in Table 1, Wang and Howe **[27]** and Eastham and Akmese **[28]**, it is possible to calculate the ferromagnetic structures ($R_0$ and $L_e$). The minimum stator teeth ($w_t$) were determined using equations presented in Bhamidi **[29]**. The windings, such as conductor number, coil number per phase, wire diameter, and current density, were calculated as shown in Hendershot and Miller **[26]**.

The stator consists of three-phase windings, with 18 coils per phase. The number of turns in each coil is 24, the wire's diameter is equal to 0.373 mm, the slot filling factor is approximately 0.45, and the slot current density is around 3.5 MA/m$^2$. Neodymium Iron Boron ($N_dF_eB$) magnets constitute the linor. They are on the surface of a massive iron and are radially magnetized. The energy product is 32 MGOe, and the coercivity is 836 kA/m.

The electromagnetic force and the magnetic inductions were determined using the finite element analyses described by Boldea and Tutelea **[30]**. Additionally, these studies were done to check the technical viability, according to the available materials and financial resources, to prototype the motor in a handmade way.

Figure 4 presents the magnetic flux and induction calculated in the FEMM (Finite Element Method Magnetics) software **[31]** at rated current to check mainly the saturation in the electrical steel. The first pole pair presented the highest induction values, and the expanded view shows around 1.35 T in the teeth (close to airgap), 1.20 T in the stator yoke, and 1.85 T in the linor yoke (small region close to the magnets).

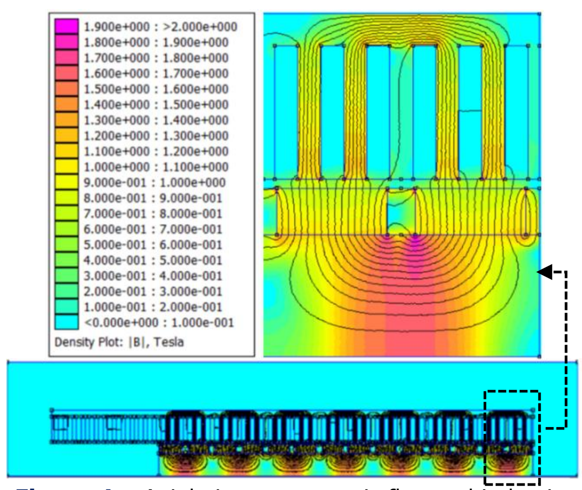
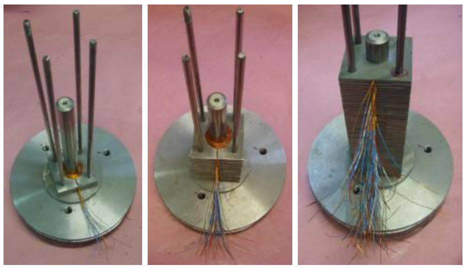


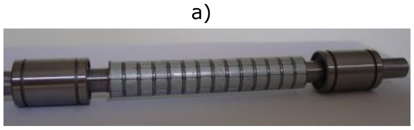

**Figure 4 –** Axial view: magnetic flux and induction at rated current and initial position of linor.
**Source:** authors.

In agreement with the values in Table 2, the prototype was handmade, requiring some adjustments due to the handcrafting process. Therefore, mass and dimensions, such as external diameter, were modified. These changes are acceptable for performing preliminary analysis to study the machine's operation. However, they are unfeasible to upper limb prostheses. The final version must meet the original requirements, using it industrially built.

Figure 5a shows the initial and final stator assembly process. The linor, with the bearings, can be observed in Figure 5b.



a)



b)

**Figure 5** – Prototype: a) Stator assembly. b) Linor with the bearings.
**Source:** authors.

## 5 RESULTS

This section presents the experimental test results, like motor parameters. After this, the machine was connected to the artificial finger to observe the movement of closing the finger (open loop).

Through the FEMM software **[31]**, resistance and inductances were evaluated and shown in Table 2. Using the RLC meter PM6303, the experimental values per phase were resistance equal to 10.80 Ω, self-inductance 3.50 mH, and mutual inductance 0.70 mH. A printed circuit board performs the series connections of the winding coils. A neutral wire allows access to each phase during the measurements. Both insertions increased the impedance of the prototype. They caused the differences between the theoretical and experimental values.

The induced motor voltages (EMFs) were measured in the stator windings using the oscilloscope TDS 3034B. There were no currents in the stator provided by the source. A rotational motor with a mechanical device moved the linor. The rated operating speed was 0.02 m/s.

The test bench and the EMF waveforms can be observed in Figures 6 and 7, respectively. The calculated EMF curves were obtained in the FEMM software, shown in Figure 7.

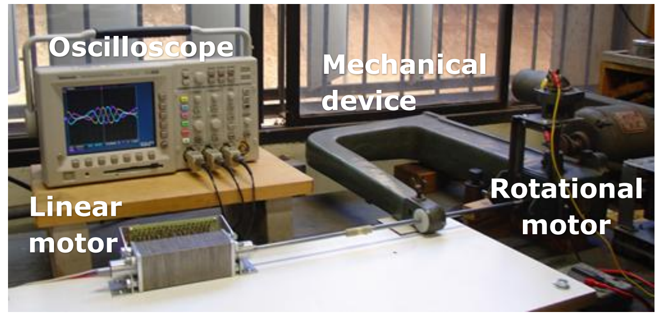



**Figure 6** – EMF test bench.
**Source:** authors.

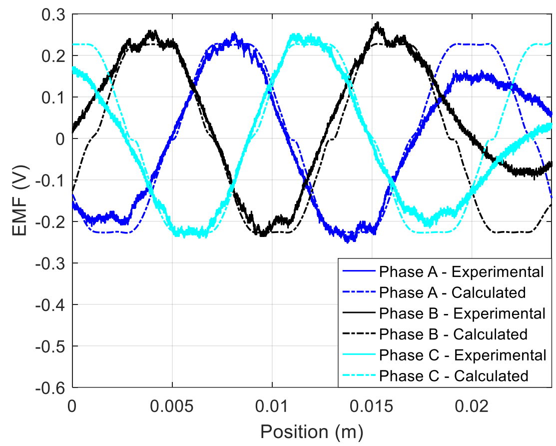



**Figure 7** – Comparisons between the experimental and calculated EMF waveforms.
**Source:** authors.

The same EMF test obtained the electromagnetic force (Figure 8). The three-phase inverter drives the linear motor, and the stator windings have currents supplied by the source. The rotational motor with the mechanical assembly performs the linear opposite movement to that of the analyzed machine (pushing it). This opposing force is a load condition test, which simulates a practical application requiring force. At one end of the motor shaft, circular parts provide force uniform distribution on the sensor (Figure 9).

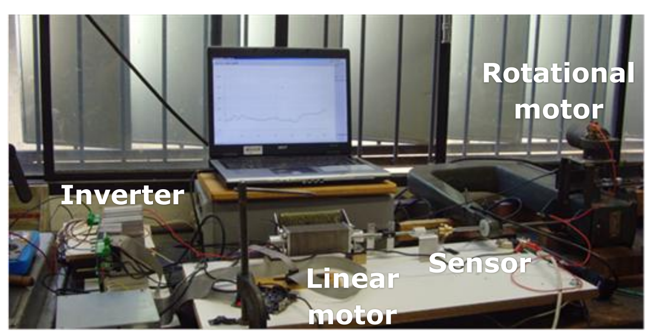



**Figure 8** – Electromagnetic force test bench.
**Source:** authors.

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The ELFTM system provides electromagnetic force measurements, which consists of a package formed by software, data acquisition hardware, and a FlexiForce® piezoresistive sensor (Figure 9). The applied force is inversely proportional to the electrical resistance **[32]**.

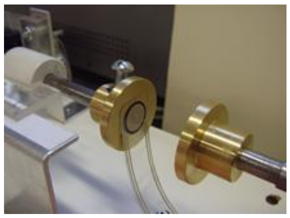


**Figure 9** – Piezoresistive force sensor *FlexiForce®*.
**Source:** authors.

Figure 10 shows the experimental force for the peak current per phase equal to 0.7 A and the calculated value in the FEMM software. Their calculated RMS (Root Mean Square) values are 10.5 N.

In the final application, the required current by the motor, per phase, will demand according to movement and object to be gripped by the finger. Controllers in a closed loop perform this adequacy.

Using FEMM software, the necessary current was calculated according to the required force by the application (Table 1). Then, the experimental current would need to be increased by 13% to achieve the RMS force around 12 N, shown in Figure 10 as the calculated required force. Therefore, the linear motor can provide the necessary force. There was no rotational motor to generate an opposing force around 12 N as a load in the test bench to repeat it.

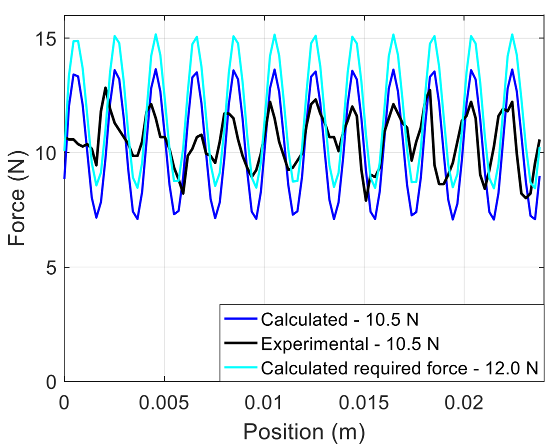


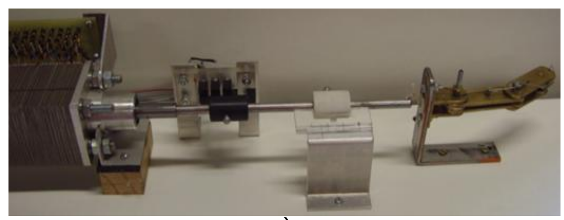

**Figure 10** – Comparisons between the experimental and calculated electromagnetic forces.
**Source:** authors.

After obtaining the experimental machine parameters, the artificial finger, which the design proposed by Zollo *et al.* **[8]**, was coupled to the actuator. The purpose of this experiment was to visually check if the linear motor was adept at performing a pinch grip movement in an open loop.

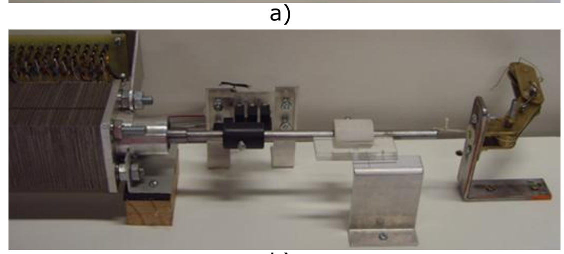
The required speed is 0.02 m/s, and the linear displacement is 1.91 cm. Considering the constant speed, closing the finger should take around 0.95 seconds.

The motor speed was manually adjusted by means of an academic inverter, setting voltage and frequency until the motor flexes the finger, taking around 0.9 s. The springs were responsible for realizing the extension movement.

Figure 11 shows three actuator positions during this observation (flexion): at the start (a), intermediate (b), and final (c) movement.



a)



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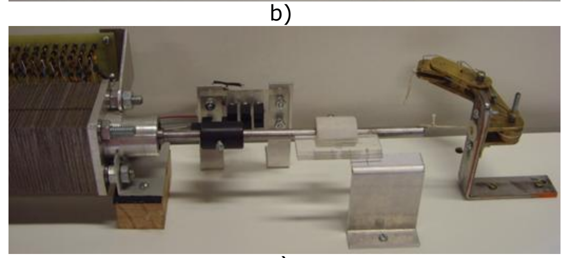

c)

**Figure 11** – Actuator position: a) start movement; b) intermediate movement; c) end movement.
**Source:** authors.

During the experiment, as expected, no sound provenance from mechanical adaptations was detected.

These results motivate further studies on applying linear motors as drivers of artificial hand prostheses. Obviously, the prototype presented herein should undergo a profound phase of mechanical optimization, including carefully selecting materials and components. However, the current results show the proposed linear motor's ability to provide the required force, speed and kinematic constraints. This can open new perspectives on prosthesis developments.

## 6 CONCLUSIONS

This work proposes linear electric motors instead of rotational motors like actuators for an upper limb prosthesis application. This replacement is motivated by the elimination of mechanical adaptation, which causes noises that are inconvenient to the patients.

The main characteristics of the linear electric motors and comparisons were presented, focused on the necessities of an artificial hand. A very preliminary benchmarking prototype was produced to test the ability of linear motoring to provide proper levels of force and speed for a finger prosthesis.

Based on the constructive, operational, and geometry features of linear electric motors, the conclusion presents that the permanent magnet synchronous machine is the best choice for the studied application. It has high electromagnetic force with few oscillations, non-complex electric control to slow speed, and high efficiency.

The experimental results are coherent with the calculated values. Besides, they show that the linear motor can attend to the force requirement and move the artificial finger.

The designed motor has some theoretical dimensions according to the materials used in the prototype, specifically the magnets. The motor volume could limit its use in prostheses that require one actuator per finger. Therefore, there are opportunities to reduce the sizes and mass by getting materials from different suppliers.

The development of new mechanisms that require linear movements can use linear motors. However, further studies are needed to customize the motor for specific parameters such as maximum speed, nominal force, maximum force, and maximum volume. Several aspects need improvement for practical applications, including the optimization of force, efficiency, mass, etc. A careful choice of materials and components is also demanded, aiming at a final version of an upper limb prosthesis.

More studies are still necessary. However, the paper demonstrates that linear motors can also be considered for prosthesis, due to the advantages provided by these driving systems.

## REFERENCES

**[1]** CORDELLA, F. *et al.* Literature review on needs of upper limb prosthesis users, **J. Front. Syst. Neurosci.**, v. 10, May 2016.

**[2]** BELTER, J. T. *et al.* Mechanical design and performance specifications of anthropomorphic prosthetic hands: a review, **J. Rehabil. Res. Dev.**, v. 50, no. 5, pp. 599-617, 2013.

**[3]** CARROZZA, M. C. *et al.* The development of a novel prosthetic hand – ongoing research and preliminary results, **IEEE/ASME Trans. Mechatronis**, v. 7, no. 2, pp. 108-114, June 2002.

**[4]** CONTROZZI, M. *et al.* The SSSA-MyHand: a dexterous lightweight myoelectric hand prosthesis, **IEEE Trans. Neural Syst. Rehabil. Eng.**, v. 25, no. 5, pp. 459-468, May 2017.

**[5]** BETTHAUSER, J. L *et al.* Limb position tolerant pattern recognition for myoelectric prosthesis control with adaptive sparse representations from extreme learning. **IEEE Trans. Biomed. Eng.**, v. 65, no. 4, pp. 770-778, April 2018.

**[6]** WITTEVEEN, H. J. B. *et al.* Vibro-and electrotactile user feedback on hand opening for myoelectric forearm prostheses. **IEEE Trans. Biomed. Eng.**, v. 59, no. 8, pp. 2219-2226, Aug. 2012.

**[7]** YAN, Y. *et al.* Design, kinematic modeling and evaluation of a novel soft prosthetic hand with abduction joints. **Medicine in novel technology and devices**, v. 15, 2022.

**[8]** ZOLLO, L. *et al.* Biomechatronic design and control of an anthropomorphic artificial hand for prosthetic and robotic applications. **IEEE/ASME Trans. Mechatronics**, v. 12, no. 4, pp. 418-429, August 2007.

**[9]** POLISIERO, M. *et al*. Design and assessment of a low-cost, electromyographically controlled, prosthetic hand. **Med. Devices**, v. 6, pp. 97-104, 2013.

**[10]** TAKAKI, Y.; OMATA, T. High-performance anthropomorphic robot hand with grasping-force-magnification mechanism. **IEEE/ASME Trans. Mechatronics**, v. 16, no. 3, pp. 583-591, Jun. 2011.

DOI: 10.25286/repa.v10i3.3110

**[11]** FOURIE, R.; STOPFORTH, R. The mechanical design of a biologically inspired prosthetic hand, the touch hand. **Proc. Pattern Recognit. Assoc. South Afr. Robot Mechatronics**, pp. 38-43, Nov. 2017.

**[12]** PYLATIUK, C.; SCHULTZ, S.; DODERLEIN, L. Results on internet survey of myoelectric prosthetic hand users. **Prosthet. Orthot. Int.**, pp. 362-70, 2007.

**[13]** BASAK, A. **Permanent-Magnet DC linear motors**. Oxford, U. K.: Clarendon Press, 1996.

**[14]** BOLDEA, I. **Linear Electric Machines, Drives, and MAGLEVs Handbook.** FL, USA: CRC Press, 2013.

**[15]** BOLDEA, I. *et al.* Linear electric machines, drives, and MAGLEVs: an overview. **IEEE Trans. Ind. Electron.**, v. 65, no. 9, pp. 7504-7515, Sep. 2018.

**[16]** GIERAS, J. F.; PIECH, J. F. **Linear synchronous motor –Transportation and automation systems.** FL, USA: CRC Press, 2000.

**[17]** TSUI, K. W. H.; CHEUNG, N. C.; YUEN, C. W. Novel modeling and damping technique for hybrid stepper motor. **IEEE Trans. Ind. Electron**., v. 56, no. 1, pp. 202-211, Jan. 2009.

**[18]** BIANCHI, N. *et al.* Tubular Linear Permanent Magnet Motors: an Overall Comparison. **IEEE Trans. Ind. Appl.**, v. 39, no. 2, pp. 466-475, April 2003.

**[19]** VERTOGEN, J. *et al.* Mechanical aspects of robot hands, active hand orthoses, and prostheses: a comparative review. **IEEE/ASME Trans. Mechatronis**, v. 26, no. 2, pp. 955-965, April 2021.

**[20]** HIROSE, S.; UMATANI, Y. The development of soft gripper for the versatile robot hand. **Mech. Mach. Theory**. v. 13, pp. 351-359, 1978.

**[21]** CUNHA, F. L.; SCHENEEBELI, H. J. A.; DYNNIKOV, V. I. Development of anthropomorphic upper limb prostheses with human-like interphalangeal and interdigital couplings. **J. Artif. Organs**, v. 24, no. 3, pp. 193-197, 2000.

**[22]** CUNHA, F. L. **Obtenção e uso dos acoplamentos cinemáticos interfalangianos e interdigitais no projeto de próteses antropomórficas para membros superiores.** Dissertation. Federal University of Espirito Santo, Vitoria, Brazil, 1999.

**[23]** WEIR, R. F. **Standard handbook of biomedical engineering & design.** New York: McGraw Hill Companies, 2004.

**[24]** BELTER, J. T.; DOLLAR, A. M. Performance Characteristics of Anthropomorphic Prosthetic Hands. **IEEE International Conference on Rehabilitation Robotics**, Zurich, Switzerland, 2011.

**[25]** McCONVILLE, J. T. *et al.* Anthropometric relationships of body and body segment moments of inertia. Dayton, Ohio: **Aerospace Medical Research Laboratory**, Wright-Patterson Air Force Base, Tech. Report; 1980.

**[26]** HENDERSHOT, J. R.; MILLER, T. J. E. **Design of brushless permanent-magnet machines.** Florida, USA: Motor Design Books LLC; 2010.

**[27]** WANG, J.; HOWE, D. Design optimization of radially magnetized, iron-cored, tubular permanent-magnet machines and drive systems. **IEEE Trans. Magn.**, v. 40, no. 5, pp. 3262-3277, Sep. 2004.

**[28]** EASTHAM, J. F.; AKMESE, R.; LAI, H. C. Optimum design of brushless tubular linear machines. **IEEE Trans. Magn.**, v. 26, no. 5, pp. 2547-2549, Sep. 1990.

**[29]** BHAMIDI, S. P. **Design of single sided linear induction motor (SLIM) using a user interactive computer program.** Dissertation. University of Missouri-Columbia, 2005.

**[30]** BOLDEA, I.; TUTELEA, L. N. **Electric machines: transients, control principles, finite element analysis, and optimal design with Matlab®.** FL, USA: CRC Press, 2022.

**[31]** MEEKER, D. **Finite element method magnetics.** 2018. Available from: http://www.femm.info/wiki/.

**[32]** TEKSCAN. **Pressure mapping, force measurement and tactile sensors.** Available from: http://www.tekscan.com. Accessed in August 2024.