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A Review of Human-Exoskeleton Kinematic Compatibility and Self-Aligning Mechanisms for Hand Exoskeleton Robots

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Abstract. To improve human-exoskeleton kinematic compatibility and mitigate misalignment, this review examines research on hand-exoskeleton compatibility through the lens of self-aligning mechanisms, following a problem-cause-tool-solution-challenge framework. First, it identifies the main sources of kinematic misalignment and their mechanical consequences, and establishes a multilevel set of evaluation metrics. It then compares methods for evaluating kinematic compatibility and clarifies the scope and complementary roles of different analytical tools. Finally, it summarises the principles, configuration types, and representative examples of self-aligning mechanisms, from which design guidelines are derived. By selectively releasing redundant constraints in the closed kinematic chain formed by the human limb and exoskeleton, self-aligning mechanisms can reduce interaction loads caused by kinematic misalignment without relying on complex sensing and control.

Keywords: hand exoskeleton robot, human-exoskeleton kinematic misalignment, kinematic compatibility, self-aligning mechanism, kinetostatics

1. Introduction

Hand exoskeleton robots have considerable application potential and clear clinical demand. In China, the incidence of stroke in 2024 was approximately 250 cases per 100,000 people, and 75-85% of stroke survivors experience upper-limb motor impairments [1].

Human-exoskeleton kinematic misalignment is a central problem affecting kinematic compatibility during rehabilitation training with hand exoskeleton robots. Various strategies have been proposed to compensate for misalignment-related degrees of freedom. This review focuses on axis self-adaptation through self-aligning mechanisms. These mechanisms introduce additional passive degrees of freedom (DOF) that allow the exoskeleton joint axes to follow the anatomical joint axes automatically. Their main advantage is that alignment is achieved passively, without sensors or a feedback control loop.

Several important gaps remain in the existing literature. Most reviews list subsystems such as actuation, sensing, and control, but do not follow a coherent progression from the sources of misalignment to analytical tools and mechanism configurations. As a result, they offer limited insight into why a mechanism is designed in a particular way. Self-aligning mechanisms have not been systematically compared by their underlying configuration principles. The location and number

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of passive degrees of freedom to be released are still determined largely through experience, and reusable design criteria remain limited.

In response to these gaps, this review makes three main contributions. First, it summarises the sources and consequences of misalignment and the methods used to quantify it, and establishes a unified set of quantitative metrics. Second, it evaluates analytical methods and tools. Third, it examines self-aligning mechanisms from their principles and representative examples to their design criteria, and derives practical design guidelines.

2. Biomechanics of kinematic misalignment and quantitative evaluation

2.1. Multiple sources of kinematic misalignment

Kinematic misalignment occurs when the exoskeleton rotational axis does not coincide with the anatomical joint axis. Fundamentally, a fixed revolute joint is used to constrain a human joint that does not behave as an ideal revolute joint. Straps and finger sleeves connect the two systems to form a closed kinematic chain, so axis offsets are converted into parasitic forces and torques acting on the limb. Human joints are not ideal hinges with geometrically fixed axes, and discrepancies between mechanical and anatomical axes are therefore unavoidable. This problem is particularly pronounced in the hand because the joints are small and closely spaced, and motion is transmitted through finger sleeves and straps. Misalignment is not a single mechanical error but a composite problem arising from multiple sources.

Kinematic misalignment can be attributed to four sources. First, morphological differences affect the position and orientation of joint axes through variations in bone geometry and soft tissue. Individual differences therefore remain even when the mechanism parameters are identical [2]. Second, kinematic differences arise because finger-joint motion combines rolling and sliding, causing the instantaneous centre of rotation (ICOR) to change with joint angle. Thus, joint alignment can refer either to static geometric alignment or to kinematic compatibility across the full range of motion (ROM). Static alignment does not guarantee compatibility throughout the movement. Third, tissue-related factors arise because the exoskeleton contacts the skin through finger sleeves and straps. Soft tissue is compressed and slips relative to the bones during movement, so the two coordinate systems do not satisfy a rigid-body constraint. Soft-tissue deformation also depends on time. During prolonged wear, the tissue continues to compress, relax, and shift relative to the bones. Initial alignment therefore does not guarantee alignment throughout the task [3]. Fourth, use-related factors arise because the actual device position can vary each time it is donned. Since hand joints are small and interface space is limited, displacements of only a few millimetres can have a marked effect [4].

2.2. Mechanical modelling of human-exoskeleton coupling

Traditional analyses represent a joint as a rigid hinge. This approach is widely used because it requires few parameters. However, it cannot describe changes in the instantaneous centre during movement. When the two axes are misaligned, it also converts kinematic errors into interface forces and torques. It is therefore suitable only as a simplified model for preliminary design.

A fixed-axis model describes joint geometry only in a static posture and cannot represent the non-fixed-centre rotation of finger joints. Human-side modelling has therefore progressed towards an ICOR trajectory model. Medical imaging or motion-capture data are used to fit the trajectory of the ICOR as a function of joint angle. The joint is represented not by a fixed axis, but by a kinematic

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function that changes with the state of motion. This representation allows dynamic misalignment between the human and exoskeleton to be defined as a function of joint angle [5]. The model captures geometric misalignment across the full range of motion and directly supports kinematic analysis and mechanism synthesis. However, it depends on individual imaging or motion-capture data, which are costly to acquire and difficult to generalise. It also does not account for soft-tissue deformation or friction.

A model of the human joint alone is insufficient to describe the actual system. The finger, exoskeleton links, and attachment interfaces form a closed kinematic chain, so the human body must be included as a moving component in the constraint system. A defined static force-transfer relationship connects the driving torque to the interface reaction force. A closed-chain coupling model treats the human skeletal chain, exoskeleton, and interfaces as one mechanism. It can describe both geometric constraints and interface loads, and can therefore be used to analyse the mechanical consequences of overconstraint. However, it has the highest modelling cost. Individual parameters must be calibrated from imaging or motion-capture data, while soft tissue and interfaces exhibit time-dependent nonlinear behaviour. Misalignment also results from the coupled effects of geometry, tissue, and donning.

The three methods differ in applicability, fidelity, and cost. A fixed-axis model has few parameters and can be solved quickly. It is suitable for preliminary mechanism and dimensional design, but offers the lowest accuracy. An ICOR trajectory model characterises geometric misalignment across the full range of motion and is suitable for kinematic analysis and mechanism synthesis. However, it depends on individual data and neglects soft tissue. A closed-chain coupling model is closest to the physical system and can estimate interface interaction loads. It is suitable for human-exoskeleton coupling and kinetostatic analysis, but has the highest modelling and parameter-acquisition cost. The methods are complementary rather than interchangeable. They answer three different questions: how the mechanism should be arranged, whether the geometry is kinematically compatible, and what mechanical consequences may result from overconstraint. No unified modelling framework currently covers all these factors. In engineering practice, the modelling level should therefore be selected according to the analysis objective. Fixed-axis models support mechanism design, ICOR trajectory models support kinematic studies, and closed-chain and interface constraints are required for human-exoskeleton coupling and load analysis.

2.3. A multilevel evaluation framework for kinematic compatibility

2.3.1. Mechanism-level quantification: direct measurement of interaction forces and torques

Mechanism-level quantification is the most direct approach. Force and torque sensors can be placed at the attachment interface, and additional loads can be evaluated using their maximum, root-mean-square, or integrated values. Sarkisian et al. asked 14 participants to perform the same task with a self-aligning mechanism in locked and unlocked conditions. After unlocking, parasitic forces and torques decreased by up to 97% [3]. This finding shows that axis misalignment can manifest directly as additional loads at the interface.

2.3.2. Interface-level quantification: measurement of pressure distribution

Compared with discrete force and torque measurements, interface-pressure measurements reveal how loads are distributed across the skin-contact region. Even when the total interaction force is the

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same, different interface designs can cause very different local pressure concentrations. Interface design therefore cannot be considered separately from mechanism kinematics [6].

2.3.3. Subjective quantification: linking comfort to objective measures

Mechanical measurements cannot fully represent subjective human experience. Comfort and pain are also core evaluation dimensions. Objective mechanical quantities must therefore be linked to subjective measures to establish a chain from mechanism parameters to mechanical consequences and user experience.

Taken together, existing studies suggest that kinematic compatibility can be evaluated quantitatively across five dimensions: parasitic forces and torques; mean and peak interface pressure; relative motion between the human and exoskeleton; ROM loss; and subjective comfort scores.

3. Methods and tools for analysing kinematic compatibility

3.1. Definition and three levels of compatibility

Human-exoskeleton kinematic compatibility is the ability of a coupled kinematic chain to avoid imposing unintended constraints on natural human movement [4]. It has three progressive levels. Geometric compatibility means that the mechanical joint axis of the exoskeleton and the anatomical joint axis occupy the same position and have the same orientation in a given posture. Kinematic compatibility means that the human joint retains its original degrees of freedom throughout the full range of motion. Mechanical compatibility means that the system produces no substantial parasitic forces or torques beyond those required to deliver the target assistive force or torque. Coincident axes provide a direct route to compatibility, but they are not the only route. A self-aligning mechanism can eliminate redundant constraints through internal motion even when the mechanical axes are not initially coincident.

3.2. Classification of compatibility approaches: static alignment and dynamic adaptation

The static-alignment approach aims to align the mechanical axis with the anatomical axis during design and donning. Anthropometric measurements are used to fit the device to the individual through adjustable links, slots, or multiple size options. The main advantages are high stiffness, low complexity, and direct transmission of the driving torque to the human joint.

The dynamic-adaptation approach does not require coincident axes during assembly. Instead, additional passive degrees of freedom are incorporated so that constraint reactions can automatically adjust the exoskeleton pose during movement. When misalignment occurs, passive motion allows the closed-chain constraints to be satisfied again, rather than requiring soft-tissue deformation to absorb the error. The two approaches are compared in Table 1.

Dynamic adaptation raises a further question: where should passive degrees of freedom be released, and how many are required? This cannot be resolved by adding joints on the basis of experience alone. The analysis must begin with the constraint state of the closed chain.

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Table 1. Comparison of static alignment and dynamic adaptation

Approach	Implementation	Response to ICOR Drift	Adaptation to Individual Differences	Response to Soft-Tissue / Donning Offsets	Main Cost
Static alignment	Anthropometric measurement, adjustable link lengths, and axis alignment during fitting	Limited	Partly compensated through size adjustment	Limited	High demands on individual adjustment and assembly accuracy
Dynamic adaptation	Additional passive translational or rotational degrees of freedom and redundant mechanisms	Strong	Strong	Partly compensated in real time	Greater mechanism complexity, size, and analytical difficulty

3.3. Methods for compatibility analysis

3.3.1. Closed-chain constraints and passive degrees of freedom

After an exoskeleton is donned, the human skeletal chain and the robot link chain form a parallel closed chain through one or more attachment points. The system becomes overconstrained when the number of independent constraints exceeds that required to define the intended motion. Rigid connections at multiple points between two chains with different kinematics can generate uncontrolled interaction forces. Since soft tissue is much less stiff than bone, the resulting deformation tends to concentrate at the interface.

The basic way to reduce overconstraint is to release an appropriate number of passive degrees of freedom in the closed chain. However, passive degrees of freedom cannot be added arbitrarily. Releasing too few constraints leaves the system overconstrained, whereas releasing too many can prevent stable transmission of the driving force. Jarrasse and Morel proposed a constructive method for allocating released degrees of freedom and demonstrated overall isostaticity [7]. Thus, self-alignment does not begin by allowing the mechanical axis to move freely. It begins by identifying and selectively releasing redundant constraints.

3.3.2. Kinematic analysis using the closed-chain vector-loop and instantaneous-centre methods

Once the degrees of freedom have been allocated, the closed-chain vector-loop method can be used to solve the kinematics. Forward kinematics derives the human joint state and interface position from the actuator input, whereas inverse kinematics derives the exoskeleton joint state from the desired motion. The human body must be included in the closed-chain model; otherwise, the analysis represents only unloaded kinematics. The instantaneous-centre method is also needed to determine which configurations best reflect physiological motion.

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Medical images have shown that finger joints do not behave as ideal fixed-axis hinges. Adjacent phalanges undergo non-fixed-centre rotation that combines rolling and sliding. Yu et al. proposed an instantaneous-radius approach to fit the equivalent ICOR and designed a crossing-type revolute pair. Validation showed that the resulting trajectories followed physiological motion more closely and that pressure on individual phalangeal segments decreased [8]. Wang et al. proposed a similar Instant Radius Method (IRM). Because the ICOR drifts continuously during flexion and extension whereas the centre of a fixed hinge remains constant, a single fixed axis cannot maintain ICOR coincidence throughout the full ROM [5]. The instantaneous-centre method can convert human data into design conditions, but it cannot describe soft-tissue deformation or friction.

The two methods are complementary rather than interchangeable, which can be summarized in Table 2. A suitable sequence is to obtain the ICOR trajectory from medical imaging or human kinematic data and use the instantaneous-centre method to establish geometric conditions. A complete closed-chain model can then be constructed, and vector-loop equations can be used to test whether redundant constraints remain throughout the full ROM. However, these methods only determine whether motion is compatible. They cannot quantify the resulting parasitic forces.

Table 2. Comparison of the closed-chain vector-loop and instantaneous-centre methods

Method	Inputs	Outputs	Best Suited For	Main Limitations
Closed-chain vector-loop method	Configuration parameters, human geometry, and actuator inputs	Joint poses, velocities, and relationships between active and passive degrees of freedom	Forward and inverse kinematics, simulation, and control for a given mechanism	Difficult to use directly for synthesising human-joint configurations
Instantaneous-centre method	Human ICOR trajectories and mechanism geometry	ICOR deviation and geometric compatibility conditions	Mechanism synthesis, rotation-centre design, and fault diagnosis	Does not directly account for compliance, friction, or actual interface forces

3.3.3. Kinematic analysis

Kinematic analysis can determine whether the degrees of freedom are sufficient and whether the system is overconstrained, but it cannot quantify the forces on the human body. In practice, the system can still move because soft tissue and structural components have finite stiffness, but additional interface reactions occur [9]. Kinetostatic analysis bridges the gap between determining whether overconstraint exists and quantifying its mechanical consequences.

Cempini et al. proposed a kinetostatic compatibility method for self-aligning mechanisms that treats the robot and human skeleton as a single coupled mechanism [10]. When passive joints are present, their force balance must also be satisfied. The generalised force at an ideal frictionless passive joint is zero. For a spring-loaded joint, the restoring torque must be included. Friction and travel limits introduce additional constraints. Jointly solving these equations yields the interface forces for a given posture and driving torque.

From a kinetostatic perspective, more passive degrees of freedom do not necessarily produce better self-alignment. Ideal compatibility requires zero interface force in non-target directions, which imposes equality constraints on the geometric parameters. If a released direction coincides with a constraint direction required to generate the target assistive torque, parasitic forces may decrease, but the mechanism may also lose the ability to deliver effective assistance. The key is to distinguish directions that must be released from those that must be retained. Self-alignment is not an absence of constraints; it is the selective application of constraints.

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Kinetostatic analysis yields the resultant forces or torques at the attachment points, whereas comfort depends on the pressure distribution across the contact area. Interface forces must therefore be mapped to contact pressure. This mapping can introduce substantial error because pressure distribution also depends on soft-tissue thickness, strap pretension, and attachment configuration. Experimental validation is required [8].

3.4. Metrics for evaluating compatibility

For rehabilitation and assistive exoskeletons, an ideal device should be barely perceptible when it is not actively providing assistance. This property is known as transparency and has three dimensions. Mechanical transparency is affected by reflected inertia, friction, and backdrivability, and can be measured using equivalent joint resistance torque. Kinematic transparency means that joint-motion characteristics remain largely unchanged before and after the device is worn. Dynamic transparency requires residual resistance to be as low as possible under zero-torque control.

Compatibility should ultimately be expressed through measurable indicators. Mechanical-transparency indicators include backdriving torque, reflected inertia, and friction torque. Kinematic-transparency indicators include joint-angle trajectory error, active ROM retention, and axis or ICOR deviation. Dynamic-transparency indicators include residual resistance torque under zero-torque control. Subjective comfort must also be included alongside these objective measures.

Direct comparisons between studies remain difficult because metric definitions, measurement locations, and test movements are inconsistent [4]. A standardised minimum set of metrics is therefore needed, together with consistent test postures, movement speeds, and normalisation methods.

4. Self-aligning mechanisms: solutions to kinematic misalignment

4.1. Principles of self-aligning mechanisms

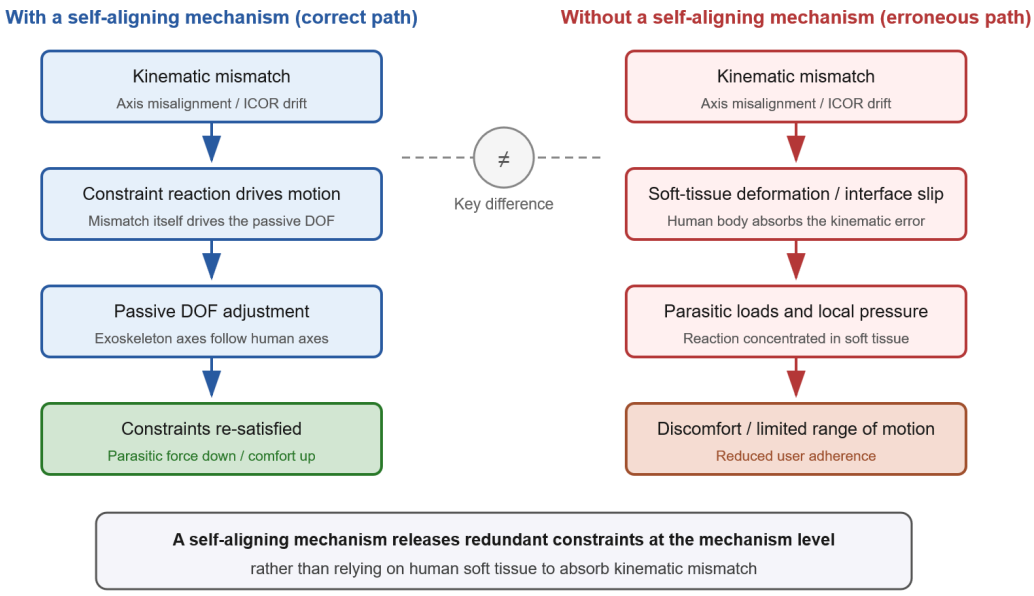


Figure 1. Comparison of the operating cycles with and without a self-aligning mechanism

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A self-aligning mechanism (SAM) introduces additional passive degrees of freedom into the coupled human-exoskeleton kinematic chain. These degrees of freedom allow the exoskeleton position, orientation, or effective motion axis to adjust passively under constraint forces, thereby reducing excess constraints caused by axis misalignment [2]. Self-alignment can be understood as a mechanical negative-feedback process driven by the misalignment itself. A trajectory mismatch first generates a constraint reaction. The component of that reaction acting along a passive-joint direction drives geometric adjustment. The reaction then decreases as redundant constraints are released. The load itself drives the alignment rather than sensors and actuators, so the mechanism can operate mechanically without closed-loop control. Figure 1 illustrates this process.

The theoretical starting point for self-alignment is not to add as many degrees of freedom as possible. It is to identify which constraints in the closed chain are redundant. Overconstraint caused by rigid connections at multiple points can generate internal constraint forces that cannot be eliminated by the actuator. Configuration design must therefore allocate both the number and the direction of constraints. The human joint must be able to compensate in directions affected by misalignment, while constraints must remain in directions needed to apply the rehabilitation torque. Self-alignment is not simply a loose mechanism. It is a directional reconstruction of the constraint system.

4.2. Examples and evidence

4.2.1. Passive degree-of-freedom release

In a hand-exoskeleton example, Sun et al. introduced spatial passive degrees of freedom at the metacarpophalangeal (MCP) joint of an index-finger exoskeleton. Rather than maintaining a predetermined axis, the mechanism allows the exoskeleton to reposition in response to human motion. The experiment showed a 65.8% reduction in the normalised sum of squared reaction forces at the MCP joint [9]. Cempini et al. extended self-alignment to the design of a full-hand system. The hand exoskeleton (HX) integrates underactuated joints, passive degrees of freedom that accommodate anthropometric variation, and self-aligning mechanisms, with compatibility, wearability, and portability as design criteria [11].

Evidence from another body region is also relevant. Sarkisian et al. used a lockable self-aligning mechanism in a powered knee exoskeleton. Fourteen participants performed the same task in locked and unlocked conditions. Unlocking reduced parasitic forces and torques by up to 97% and improved task performance by up to 38% [3]. The within-subject comparison directly isolated the effect of self-alignment.

4.2.2. Geometric matching

This approach directly changes the geometry of the exoskeleton joint so that its inherent trajectory more closely follows the trajectory of the human joint. Imaging showed that finger joints undergo non-fixed-centre rotation. Yu et al. used an instantaneous-radius approach to obtain continuous ICOR trajectories and designed a crossing-type revolute pair. The resulting fingertip trajectories were closer to physiological trajectories, and pressure on individual phalangeal segments decreased. Wang et al. used equivalent ICORs to construct biomimetic kinematic pairs through the Instant Radius Method. Mean pressure decreased by approximately 15-25%, and peak pressure decreased by approximately 20-30% [5].

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Compared with passive degree-of-freedom release, geometric matching approximates the human ICOR using an equivalent ICOR. This approach offers greater determinacy but depends on model accuracy. By contrast, passive degree-of-freedom release allows the mechanism to find a compatible position through passive motion. It can better accommodate individual differences, but its force-transmission characteristics are more complex.

4.2.3. Hybrid designs

The I-Phlex kinematic chain developed by Peperoni et al. includes a remote centre of motion virtually located at the MCP joint. Passive joints at the rear form the self-aligning component and reduce shear and longitudinal parasitic loads during flexion and extension. This two-stage design first approximates the geometry and then passively compensates for residual mismatch. The remote-centre structure places the effective rotation centre near the anatomical joint, while the passive joints absorb differences in body dimensions, donning errors, and residual drift. I-Phlex is also one of the few mechanisms tested in a real clinical setting. Following a single intervention in six patients with right-hand trauma, the median passive range of motion (PROM) improved by 5.88% and the median active range of motion (AROM) improved by 11.11%, with no serious adverse events [12]. However, the study had no control group. It therefore supports feasibility but does not establish long-term efficacy.

Evidence from other body regions is also available. Li et al. developed a spatial self-aligning knee exoskeleton that accommodates both knee flexion and extension and hip internal and external rotation. Its interaction forces and torques were lower than those of existing exoskeletons. This result suggests that self-alignment can address combined spatial misalignment involving changes in both position and orientation [13].

Table 3. Representative self-aligning mechanisms and comparative evidence

Anatomical Site	Main Principle	Main Configuration	Comparison Method	Experimental Subjects	Key Evidence
Index-finger MCP joint	Release of degrees of freedom	Spatial passive self-aligning mechanism	Compared with an existing design	Prototype and experimental validation	Normalised sum of squared reaction forces reduced by 65.8%
Fingers and thumb	Release of degrees of freedom	Passive degrees of freedom plus a dedicated self-aligning mechanism	Design and adaptability validation	Prototype and experimental validation	Adaptation to anthropometric variation and axis self-alignment demonstrated
Finger joints	Geometric matching	Equivalent ICOR and crossing-type revolute pair	Original and biomimetic structures compared	Experimental validation	Improved fit to physiological trajectories and reduced pressure on phalangeal segments
MCP joint	Hybrid design	Remote centre plus revolute-prismatic-revolute (RPR) self-aligning mechanism	No randomised control group	Six patients	PROM improved by 5.88%; AROM improved by 11.11%; no serious adverse events

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Table 3. (continued)

Knee	Release of degrees of freedom	Lockable self-aligning mechanism	Within-subject locked/unlocked comparison	14 healthy participants	Parasitic loads reduced by up to 97%; comfort improved by up to 15.3%
Knee and hip	Spatial degree-of-freedom release	Spatial self-aligning mechanism	Compared with existing exoskeletons	Experimental validation	Reduced interaction forces and torques during knee flexion/extension and hip rotation

Table 3 shows broadly consistent mechanical evidence across the fingers, the whole hand, the knee, and the hip. Appropriately configured self-aligning degrees of freedom can reduce additional loads. However, the strength of validation varies. Lower-limb studies include rigorous locked-versus-unlocked comparisons, whereas most hand studies remain at the mechanism-validation or small pilot-study stage.

4.3. Design considerations and limitations

4.3.1. Selective constraints and parameter design

Design should not begin by adding a passive slider or hinge. The first step is to determine whether the closed chain is overconstrained and how many constraints need to be released. The direction of the passive degrees of freedom should then be selected according to the source of misalignment. Releasing constraints necessarily changes the force-transmission space. If the released direction coincides with a constraint direction required for the target assistive torque, parasitic forces may decrease, but the mechanism may lose the ability to deliver effective assistance [10]. The design must therefore distinguish directions in which misalignment must be accommodated from directions that must be retained for force transmission.

Passive joints are also affected by restoring stiffness, travel, and mechanical stops. Greater restoring stiffness improves positional certainty, but a larger constraint torque is then required for alignment. Lower stiffness reduces residual parasitic forces, but may leave the mechanism loose. The literature does not yet provide a unified quantitative range for stiffness. Travel determines the maximum misalignment that can be absorbed. Once a joint reaches its travel limit, the system behaves like a rigid closed chain. Mechanical stops also prevent singular configurations and interference with adjacent fingers.

4.3.2. Coordinated design of the attachment interface and mechanism

Self-alignment acts at the mechanism level, but its effect must be transmitted to the skeleton through the human-robot attachment interface. The attachment system must transmit interaction forces while maintaining relative axis alignment. Insufficient stiffness allows excessive relative motion, whereas excessive rigidity concentrates misalignment loads on the human body [6]. Mechanism-level self-alignment and interface-level compliance are therefore complementary rather than interchangeable. Passive degrees of freedom provide predictable geometric compensation, while the interface accommodates only small soft-tissue deformations. If straps allow excessive uncontrolled slip, soft-tissue displacement dissipates the assistive force. If the interface is completely rigid, residual misalignment is converted into local compressive and shear stresses.

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5. Challenges and future prospects

5.1. Key challenges

The inherent limitations of self-aligning mechanisms mainly arise from their passive degrees of freedom. First, quantitative design ranges for restoring stiffness and passive travel are lacking. Current designs rely heavily on prototype adjustment and empirical trial and error, so the required parameters cannot be derived directly from the magnitude of misalignment. Second, friction and backlash can disable passive motion under low loads. When the constraint torque caused by misalignment falls below the static-friction threshold of a joint, the mechanism behaves like a rigid connection. Third, additional degrees of freedom increase size and mass. This can cause spatial interference when mechanisms are fitted to several fingers at once. Finally, mechanism-level self-alignment cannot replace attachment-interface design. Soft-tissue deformation and slippage during donning can still cause discomfort even after geometric axes have been aligned. These limitations are inherent to the approach, but they may be mitigated through unified kinetostatic modelling, parameterised design ranges, and coordinated design of the interface and mechanism.

The field of compatibility research also faces broader challenges. First, evaluation criteria are inconsistent, which prevents evidence from different studies from being accumulated and compared. Second, general criteria for personalisation are lacking. The quantitative relationship between passive travel and the magnitude of individual differences remains unclear. Third, clinical validation is insufficient. Almost all current evidence comes from healthy participants or prototype testing. Only a small number of mechanisms have been tested in patients, and those studies lack control groups. The effectiveness of self-alignment in patient populations therefore remains largely unverified. These challenges cannot be resolved by an individual study alone and require field-wide standards.

5.2. Future research directions

Future research can address the limitations and challenges described above in three main directions.

First, quantitative design ranges should be established. A quantitative mapping among misalignment magnitude, passive travel, and restoring stiffness would shift parameter selection from empirical trial and error towards theory-driven design and help establish criteria for personalisation.

Second, a comprehensive standardised evaluation framework is needed. A minimum set of metrics should focus on geometric misalignment, parasitic forces, peak interface pressure, and active ROM retention. Locked-versus-unlocked comparisons should be adopted more widely so that the contribution of self-alignment can be separated from overall system performance and accumulated across studies.

Third, clinical validation should be conducted in real patient populations. The number of clinical studies remains limited. Validated configurations could be evaluated in clinical research to determine how pathological conditions, including spasticity, increased muscle tone, and sensory impairment, alter the nature of misalignment.

6. Conclusion

Human-exoskeleton kinematic misalignment arises from four sources: individual differences, ICOR drift, soft-tissue deformation, and donning offsets. These factors are converted through the coupled human-exoskeleton chain into parasitic forces and concentrated interface pressure. The closed-chain

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vector-loop method identifies redundant constraints, the instantaneous-centre method analyses ICOR matching, and kinetostatic analysis reveals the mechanical consequences of overconstraint. Each method has limitations, and the methods are complementary. The central principle of self-aligning mechanisms is selective constraint rather than unrestricted motion. Redundant degrees of freedom are released in directions affected by misalignment, while constraints are retained in directions required for assistance. This principle provides a theoretical basis and practical direction for future research on improving human-exoskeleton kinematic compatibility.

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