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Biofeedback-Based Adaptive Furniture Design: Sensor Technologies for Therapeutic Interiors

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Abstract

Sensors, integrated with biofeedback systems, AI, and IoT technologies, provide adaptive features to furniture by offering real-time feedback to users' needs. In this context, using sensors in adaptive furniture has emerged as a contemporary research area, as it may influence not only physical requirements but also psychological well-being. This study asks: "Do sensors in adaptive furniture create therapeutic effects that support psychological well-being, and how do these effects differ by sensor type?" User interaction-oriented sensors (pressure, force, touch, motion), identified through purposive sampling, were evaluated using visual and printed secondary data sources. Data were analyzed under the themes of data type collected, furniture response, and therapeutic effect. Results indicate that pressure sensors contribute to postural awareness; force sensors to physical comfort; touch sensors to the sense of security; and motion sensors to the perception of safety and support for independent living.
Keywords: Adaptive Furniture; Biofeedback System; Smart Furniture Design; Sensor Technologies; Therapeutic Interiors.

1. Introduction

Contemporary technology presents a comprehensive technological paradigm through digital system infrastructures developed within the framework of the Internet of Things (IoT) and Industry 4.0. This paradigm transforms physical objects into intelligent systems capable of generating data, communicating with users, and consequently producing adaptive responses (Frischer, 2020). The transformation of physical objects into smart systems offers significant opportunities for users by enabling the emergence of new usage scenarios (Krejcar, 2019). The integration of intelligent systems across multiple spatial scales, ranging from urban environments to furniture-level applications, not only shapes but also supports users' lifestyles, behaviors, and preferences. In this context, it is increasingly important that interior furniture designs are designed in alignment with evolving user expectations and are embedded with intelligent system infrastructures appropriate to their spatial context (Xu, 2024).

The convergence of the Internet of Things (IoT), ambient intelligence, and human-centered design (HCD) transform furniture from a passive interior object into a dynamic and interactive system (Fewella, 2024: 2; Mimoso et al., 2025: 2). Moreover, object-based guidance mediated through sensory modalities such as vision, hearing, smell, and touch has been shown to activate behavioral and social norms that balance individual and collective concerns. Such interventions, mediated through everyday objects, contribute to the regulation of both individual and societal issues (Cash et al., 2017). In recent years, a growing body of research has emphasized technology-supported mental health design, ranging from conceptual syntheses of emotional health, behavioral regulation, awareness, and psychosocial technologies to user engagement strategies (Farral et al., 2023: 2). By integrating emotion regulation strategies-including situation selection, situation modification, attentional deployment, cognitive change, and response modulation (Gross, 2015)-these technologies aim to implement didactic and experiential mechanisms for offline prevention or remediation, in-situ intervention, and embodied skill training (Petr et al., 2022). Such technologies, which integrate emotion regulation frameworks (Gross, 2015), primarily aim to enhance users' psychosocial well-being (Farral et al., 2023). In this context, the responsiveness of spaces and objects to the user's immediate physiological state introduces a novel therapeutic design approach. Within the scope of this study, therapeutic effect is defined as the potential of furniture to improve the user's current psycho-physiological state through adaptive modifications in its physical form or function, based on the processing of biofeedback data such as muscle tension and heart rate variability.

Although existing literature highlights the potential of biofeedback-based adaptive systems (Fewella, 2024; Xu, 2024), there is a notable lack of studies that integrate user experience with the therapeutic dimension of furniture design. This

gap particularly limits the development of a holistic understanding within the field of interior architecture regarding how the interaction between technology and human psychology can be meaningfully directed through design.
Based on this necessity, the present study is grounded in the assumption that adaptive furniture equipped with artificial intelligence and IoT-based sensors can generate a responsive feedback loop aligned with the user's psycho-physiological state, thereby contributing meaningfully to psychosocial recovery processes. The primary aim of the study is to propose a multi-layered, biofeedback-based conceptual framework that enables such interaction. In doing so, the study extends adaptive furniture designs beyond their technical functionality and conceptualizes their embodied and responsive interaction processes with users through an interdisciplinary perspective.

1.1 Biofeedback System

Biofeedback is a method that provides real-time biological information to individuals regarding physiological and biomechanical processes that they are typically unaware of or unable to consciously control. This approach is based on the acquisition of data from sensors measuring bodily functions, the processing of these data, and their return to the user through visual, auditory, or tactile feedback signals (Kos & Umek, 2018).
Biofeedback methods are generally classified into two main categories: physiological and biomechanical biofeedback. Physiological biofeedback focuses on signals derived from the neuromuscular, cardiovascular, and respiratory systems of the human body. Within the neuromuscular domain, it is primarily used for muscle re-education, while in the cardiovascular and respiratory domains it is applied in the management of conditions such as asthma and cardiac disorders (Giggins et al., 2013). Biomechanical biofeedback, on the other hand, involves the measurement of movement, postural control, and forces generated by the body (Kos & Umek, 2018). Biomechanical feedback is particularly effective in balance training, gait rehabilitation, and postural correction. It enables real-time measurement of joint range of motion and kinematics and is commonly used to reduce knee hyperextension after stroke or to improve walking speed.
The closed-loop feedback process (Figure 1) refers to a cyclical control mechanism in which physiological or biomechanical data obtained from the user through sensors are analyzed, and corresponding feedback is generated by the system. As a result, changes in the user's psycho-physiological state are continuously re-detected, enabling ongoing system adaptation (Kos & Umek, 2018).
In rehabilitation contexts, biofeedback aims to enable individuals to gain voluntary control over their bodily processes through external informational cues, thereby facilitating the reacquisition of normal movement patterns (Giggins et al., 2013: 2). Biofeedback accelerates motor learning by allowing users to immediately recognize and correct erroneous movements, thereby activating the learning loop. Additionally, through virtual reality and gamified applications, it enhances motivation and adherence to therapeutic programs, while sensor-based systems provide clinicians with objective and high-resolution data regarding patient progress. Once individuals learn to use biofeedback devices, they can perform exercises correctly without continuous supervision, thereby increasing both independence and system efficiency. In this respect, biofeedback transforms rehabilitation from a passive process into an active learning process, enabling individuals to gain greater control over their own recovery trajectories.
Biofeedback can also provide real-time, adaptive information designed to overcome challenges related to self-awareness through operant conditioning-based techniques (Petr et al., 2022). Commonly used strategies include graphical, explanatory, artistic, and ambient screen-based representations, which allow users to perceive their physiological states as part of meaningful interactive experiences (Zhida et al., 2017). Interaction in this context emerges through self-regulation processes in which information is internalized and cognitively integrated, with users often preferring visualizations that reduce cognitive load and simplify complex physiological data.
Morphing or shape-changing physicalizations can further extend information transfer by guiding users toward physiological states through embodied and often subconscious bodily changes (Yvonne et al., 2015). In this way, embodied skill training based on operant conditioning can be implemented to enhance emotional regulation, enabling bodily awareness and control to be learned through lived physical experience (Farral et al., 2023). Collectively, these characteristics reposition biofeedback technology from a purely clinical intervention tool to a powerful interaction system that can be embedded into everyday objects. From this perspective, the following section will examine how this technological infrastructure can be transferred to adaptive furniture designs and will outline the fundamental principles of responsive interaction between furniture and user.

1.2. Adaptive Furniture Design and Therapeutic Effects

Adaptive design is a holistic design approach that enables products to be transformed into different configurations through modular structures during the production process and to be refunctionalized in response to changing user requirements throughout the usage process (Gu et al., 2009). This approach is regarded not only as a mechanism based on the physical transformability of the product but also as a system-based paradigm relying on an interaction mechanism continuously updated through user feedback (Gu et al., 2004; Li et al., 2008). The primary objective of adaptive design is to ensure that the product maintains its functionality by adapting to changing contexts and needs, thereby extending its lifespan and establishing a structure compatible with sustainability principles (Kasarda et al., 2007). In this context, the concept of adaptability is not limited solely to technical flexibility; it also encompasses multidimensional characteristics such as safety, durability, environmental compatibility, and adaptation to the context of use (Uckun et al., 2014). The adaptive product design model proposed by Gu et al. (2004) systematically addresses this process through stages including the identification of requirements, the development of modular structures, the construction of system architecture, user interface design, prototyping, and evaluation. Accordingly, adaptive furniture design is considered a dynamic system capable of perceiving changing user requirements and generating responses to these needs; it evolves beyond being merely a functional product into a design approach that remains in continuous interaction with the user and can restructure itself through this interaction (Yolcu, 2026).

In the literature on environmental psychology and healing environments, the concept of therapeutic effect is predominantly defined by the potential of environmental components to engender a sense of security in users, alleviate stress, reinforce the perception of control, and facilitate social interaction (Ulrich, 1984; Carlsen, 1988). Framed by this perspective, furniture is addressed not merely as a functional furnishing but as a therapeutic interior component that contributes to the re-establishment of daily routines, the cultivation of spatial belonging, and the support of psychosocial recovery processes. In this respect, adaptive furniture design necessitates a holistic approach to adaptability that encompasses technical safety and design flexibility alongside explicit therapeutic impact

1.3. Sensor Use in Furniture Design

Sensors are technological devices that measure physical variables such as temperature, light, pressure, and motion and convert these data into processable and useful signals. Industries rely on sensors related to sound, motion, proximity, chemicals, electricity, biology, optics, pressure, force, and temperature (Fewella, 2024: 5). Fundamentally, they function as data collection tools by detecting and quantifying changes in the environment. They constitute the first and most essential pillar of smart furniture designs.

Sensors used in smart and adaptive furniture design are classified according to their purposes, including detecting user behaviors, monitoring environmental conditions, and collecting data regarding physiological states. In literature, the most used sensor types in furniture design are grouped under five main categories: (i) user behavior and interaction-oriented sensors, (ii) physiological and biometric sensors, (iii) environmental perception sensors, (iv) safety and stability sensors, and (v) location and identity recognition sensors.

Human-centered and interaction-oriented sensors are designed to detect the user's physical interaction with furniture as well as the way the furniture is used. Within the category of user behavior and interaction-oriented sensors, pressure sensors, force sensors, touch sensors, and motion sensors are the most employed technologies.

The integration of pressure sensors into furniture design enables the detection of users' sitting and lying positions, contact points with the furniture, weight distribution, and posture changes. Through pressure sensors, ergonomic analyses of users can be conducted, and the duration and frequency of furniture use can be identified. Similarly, force sensors analyze user movements by detecting the magnitude and direction of the load applied to the furniture. The use of force sensors in furniture designs contributes to maintaining structural balance and enables the furniture to regain its original state without collapsing, deforming, or losing functionality when exposed to external impacts.

The incorporation of touch sensors into furniture design makes it possible to identify surface contact, touch frequency, and different forms of user interaction with furniture. Through interactive furniture surfaces, feedback mechanisms can be activated and maintained. Likewise, the inclusion of motion sensors in furniture design allows the detection of the user's presence within the space, movement patterns, and interactions established with the furniture. Motion sensors facilitate the monitoring of usage intensity while also increasing the perceptibility and responsiveness of furniture within interior environments.

2. Materials and Methods

2.1 Research Aim and Research Questions

This study examines the potential of sensor-based adaptive furniture designs to generate therapeutic effects on users within the framework of a biofeedback approach. Rather than focusing on the experimental measurement of therapeutic outcomes, the study aims to conceptually discuss how sensor-driven interaction processes between adaptive furniture and users may support psychophysiological regulation.

In this context, the study conceptualizes adaptive furniture designs enhanced with artificial intelligence (AI), the Internet of Things (IoT), and sensor technologies as interactive spatial interfaces capable of perceiving user behaviors, interpreting collected data, and generating responsive outputs according to user needs.

The primary research question is formulated as follows:

"Can sensor-based adaptive furniture designs support therapeutic outcomes, and how do these potential outcomes vary according to sensor type?"

In line with this main question, the study aims to: (i)reinterpret the perception–interpretation–feedback loop defined in biofeedback systems within the context of adaptive furniture, (ii)examine the role of sensor technologies in producing user-responsive furniture designs, (iii) discuss the potential therapeutic effects of feedback mechanisms generated by adaptive furniture designs.

2.2. Research Design

The study adopts a qualitative and conceptual research approach. No experimental user testing or physiological measurements were conducted; instead, adaptive furniture designs were evaluated analytically through existing literature, design cases, and technology-based applications.

The methodological framework of the study is structured in relation to the fundamental operational logic of biofeedback systems. Accordingly, the research focuses on sensor systems capable of direct interaction with users in adaptive furniture contexts.

A purposive sampling strategy was employed to select four sensor types that are widely used in adaptive furniture design: (i) pressure sensors (ii) force sensors, (iii) touch sensors, (iv) motion sensors. These sensor types were included in the study due to their ability to directly detect user behavior and physical interaction, as well as their potential to generate biofeedback-based adaptive responses within furniture designs.

Although touch and motion sensors are conceptually included among the commonly referenced sensor types in adaptive furniture literature, they are not treated as independent analytical categories in the findings section of this study. This exclusion is grounded in two primary considerations. First, touch sensors fundamentally rely on the same physical detection mechanism as pressure sensors (surface contact), and their therapeutic outcomes—such as enhancing the sense of security—are conceptually derived from analogous data streams. Similarly, motion sensors primarily detect positional changes and body displacement, which are inherently captured and interpreted through combined force and pressure distribution analyses. Second, the existing body of peer-reviewed literature predominantly addresses touch and motion sensors in the context of wearable technologies or ambient intelligence systems rather than stationary furniture interfaces, resulting in a limited number of empirical studies that specifically investigate their therapeutic effects within furniture-interaction contexts. Therefore, the detailed thematic analysis in the following sections concentrates on pressure and force sensors as the two primary categories that comprehensively encompass the core physical interactions between user and furniture, while touch and motion sensors are acknowledged as auxiliary inputs to be explored in future empirical research (Figure 1).

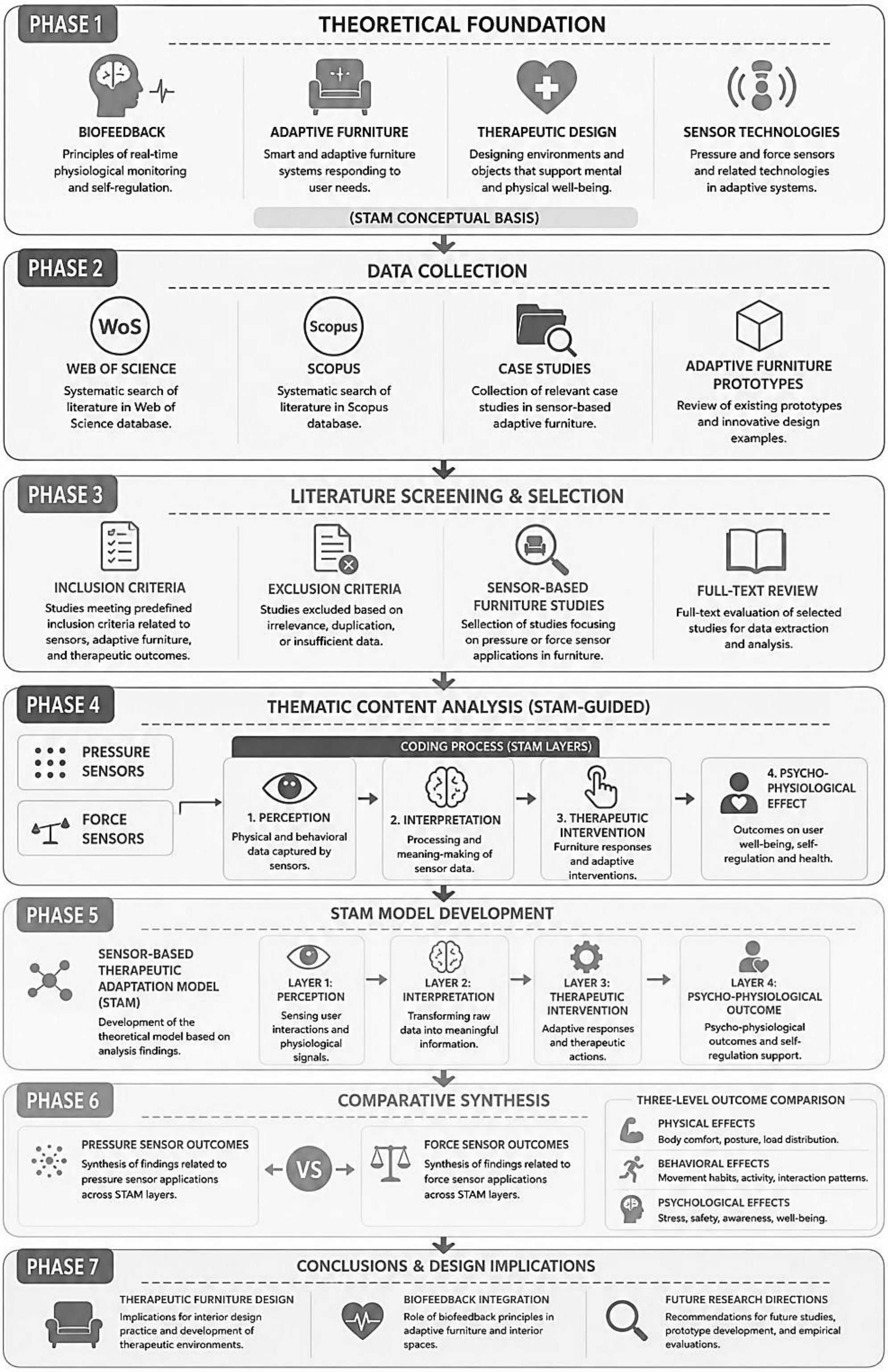

Figure 1. Structure of the Study (Developed by the Authors).

2.3. Data Collection & Data Analysis

Secondary data sources were utilized in this study. In this context, full-text accessible academic publications retrieved from the Web of Science (WoS) and Scopus databases were examined. In addition, academic articles, smart furniture applications, product documentation, design prototypes, as well as visual and technical materials were included in the data collection process. The collected data were analyzed thematically with a focus on: the types of data collected by sensors, how these data are interpreted within adaptive systems, how furniture generates adaptive responses, and the potential therapeutic effects of these responses on users. In particular, studies addressing user behavior, posture control, physical comfort, motion detection, and interaction-oriented adaptive systems were included in the scope of analysis.

The analytical framework of the study was developed based on the fundamental operational principles of biofeedback systems. Biofeedback systems operate through a cyclical structure consisting of the detection of users' physiological or behavioral data, the interpretation of this data by the system, the generation of feedback directed to the user, and the resulting psychophysiological effect on the user. Accordingly, within the scope of this study, adaptive furniture designs are conceptualized as a spatial and object-scale extension of the biofeedback mechanism. The processing of user data collected through sensors by adaptive furniture designs and the corresponding generation of physical or sensory responses are aligned with the closed-loop logic of biofeedback systems.

2.4. Sensor-Based Therapeutic Adaptation Model for Furniture Design

To provide a conceptual framework for understanding how adaptive furniture designs may support psycho-physiological regulation through biofeedback mechanisms, this study proposes the Sensor-Based Therapeutic Adaptation Model (STAM). STAM conceptualizes adaptive furniture equipped with sensor technologies, Artificial Intelligence (AI), and Internet of Things (IoT) infrastructures as interactive therapeutic interfaces capable of perceiving user conditions, interpreting collected data, generating adaptive responses, and supporting self-regulation processes (Figure 3).

Unlike conventional furniture, which primarily serves functional and ergonomic purposes, STAM positions furniture as an active environmental component that continuously exchanges information with the user. The model is grounded in biofeedback theory, which suggests that physiological and behavioral information can be monitored, interpreted, and fed back to individuals in ways that facilitate awareness, behavioral adaptation, and psycho-physiological regulation. Within this framework, adaptive furniture is conceptualized as a spatial extension of the biofeedback loop, transforming sensor-generated information into environmental interventions.

STAM is structured as a closed-loop system consisting of four interconnected layers: (i) perception layer, (ii) ınterpretation layer, (iii) therapeutic response layer, and (iv) psycho-physiological outcome layer (Figure 2). Together, these layers establish a continuous cycle of sensing, interpretation, intervention, and feedback.

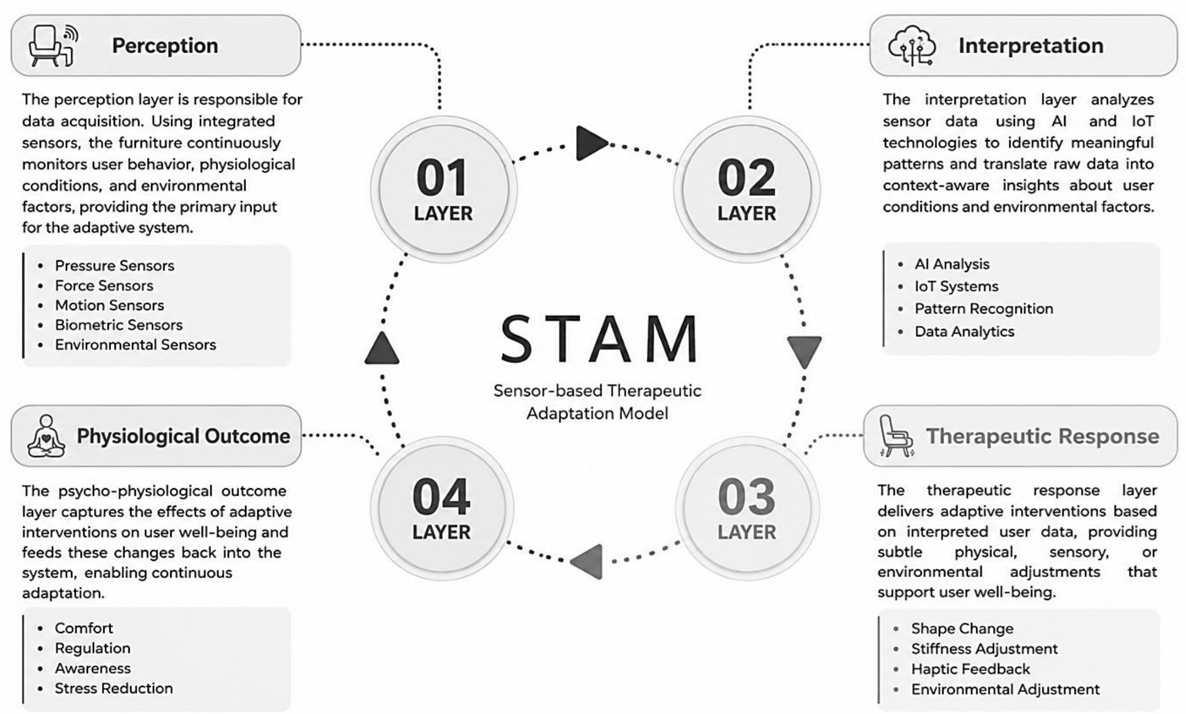

Figure 2. The four-layer structure of the Sensor-Based Therapeutic Adaptation Model (STAM) (Developed by the Authors).

2.4.1 Perception Layer

The perception layer represents the data acquisition stage of the model. Through integrated sensors -including pressure, force, motion, biometric, and environmental sensors- the furniture continuously monitors user behavior, physiological conditions, and environmental variables. Data collected at this stage may include posture, body movement, inactivity duration, contact patterns, physiological indicators, and environmental conditions. This layer provides the primary input for the adaptive system.

2.4.2 Interpretation Layer

The interpretation layer constitutes the cognitive component of STAM. Sensor-generated data are processed through AI-supported analytical systems and IoT infrastructures to identify meaningful patterns related to user conditions. At this stage, raw data are translated into interpretable states such as postural imbalance, prolonged inactivity, physical discomfort, stress-related indicators, or environmental incompatibilities. Consequently, the system moves beyond simple monitoring and develops the capacity to generate context-sensitive interpretations.

2.4.3 Therapeutic Response Layer

The therapeutic response layer refers to the stage at which adaptive furniture generates physical, sensory, or environmental interventions based on interpreted user data. These responses may include modifications in furniture configuration, support stiffness adjustment, micro-movements, haptic feedback, ambient lighting changes, or other adaptive environmental responses. Rather than functioning as explicit corrective mechanisms, these interventions are designed to operate as subtle environmental supports that facilitate user well-being.

2.4.4. Psycho-Physiological Outcome Layer

The psycho-physiological outcome layer represents the effects of adaptive interventions on the user. Potential outcomes include increased bodily awareness, improved postural regulation, enhanced comfort, reduced stress, strengthened feelings of safety and control, and support for emotional regulation processes. Importantly, changes occurring at this stage become new inputs for the perception layer, thereby completing the feedback loop and enabling continuous system adaptation.Accordingly, STAM conceptualizes adaptive furniture not merely as a responsive technological artifact but as a therapeutic environmental interface that continuously mediates interactions between user states and spatial conditions. Through its four-layer structure, the model provides a theoretical framework for examining how sensor-based furniture designs may contribute to psycho-physiological well-being within interior environments.

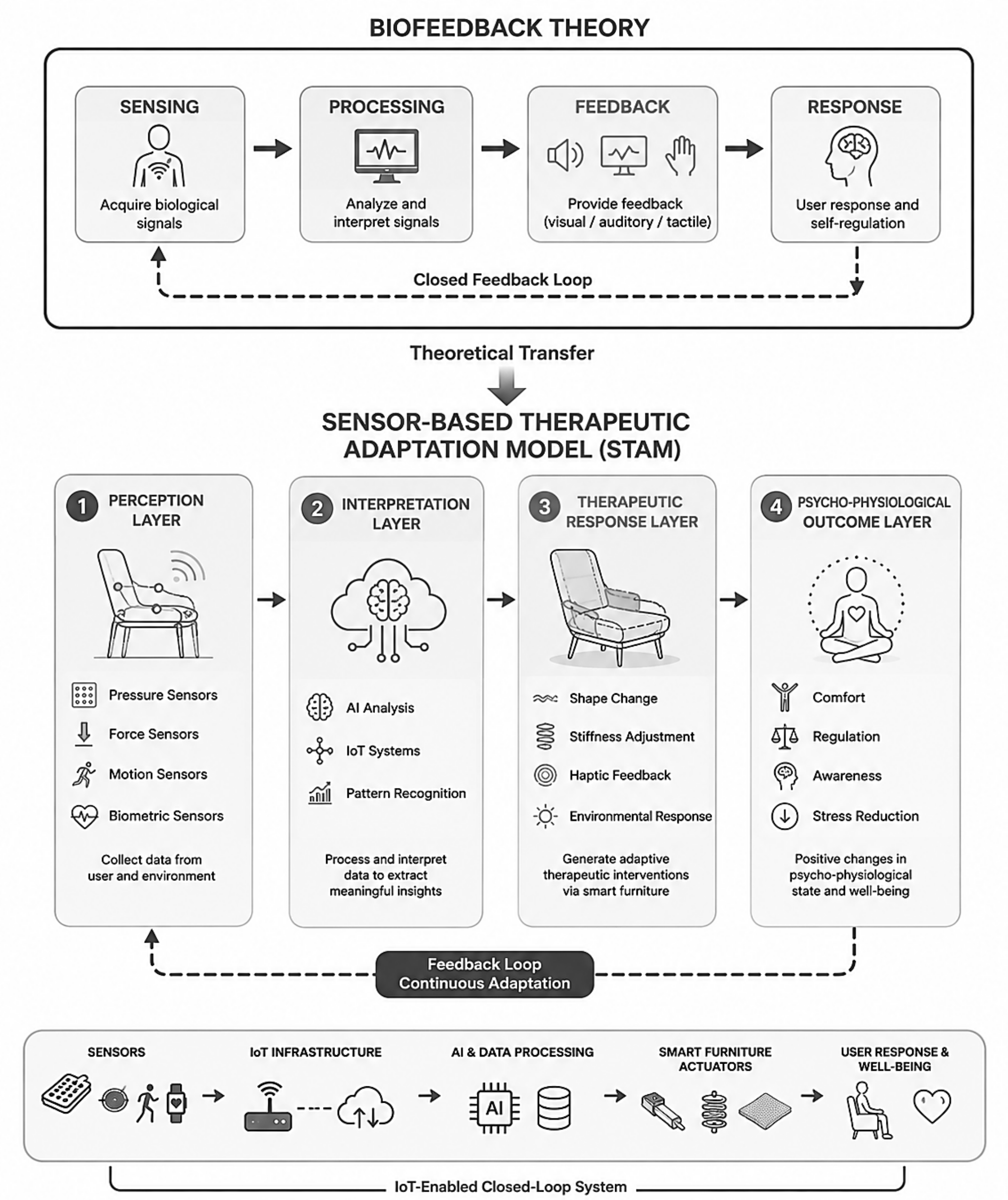

Figure 3. Sensor-Based Therapeutic Adaptation Model (STAM) and Biofeedback System (Developed by the Authors).

2.5 Scope and Limitations of the Study

This study is conceptual and analytical in nature. No experimental implementation, user testing, or biometric measurements were conducted within its scope. Therefore, the therapeutic effects discussed are addressed at a theoretical level, drawing on existing literature on biofeedback, smart systems, and adaptive furniture design.

Nevertheless, the study aims to propose a conceptual framework that explores the relationship between sensor technologies and therapeutic interior design. In this regard, it seeks to provide a foundational basis for future research in both design education and user-experience-based experimental studies.

3. Findings

3.1 Adaptive Furniture Design Based on Pressure Sensors

3.1.1 Perception of the User

The perception layer refers to the stage at which physical and behavioral data related to the user are directly collected through pressure sensors. In furniture design, pressure sensors constitute fundamental components that transform conventional furniture into “smart” systems capable of detecting user actions and needs (Mimoso et al., 2025: 2). Through these sensors, individuals’ sitting habits can be monitored, health conditions can be tracked, and the physical form of furniture can be adjusted to enhance user comfort (Vlaović et al., 2022: 1). Moreover, these systems can detect conditions such as skipped meals, insufficient sleep, or prolonged inactivity and may enable alert mechanisms that notify remote family members in case of risk (Lim et al., 2008: 5188).

Pressure sensors enable detailed monitoring of the interaction between furniture and user. Sensor arrays integrated into the seat and backrest of office chairs can classify sitting postures in real time (e.g., upright, leaning forward, or cross-legged positions) (Hong et al., 2021: 265), while systems based on pressure distribution analysis and human skeletal modeling allow for the estimation of body posture during sleep (Harada et al., 1999). In addition, pressure sensors can facilitate the monitoring of physiological parameters such as heart rate, respiration rate, and blood oxygen level without direct contact (Vlaović et al., 2021: 235), while acoustic pressure sensors (ECM) integrated into furniture provide long-term heart sound monitoring capabilities (Wang et al., 2021: 2). Furthermore, high-sensitivity FSR arrays or acoustic pressure sensors can detect micro-movements of the body, enabling the measurement of vital physiological parameters (Vlaović et al., 2021: 228).

Although sensors are traditionally placed on seating surfaces, some designs integrate them beneath chair legs, enabling smart functionality without interfering with upholstery systems (Cheng et al., 2013: 82). This approach allows even subtle movements such as keyboard typing or head nodding to be detected. Similarly, the GravitySpace system tracks user identity and spatial position by analyzing pressure traces generated on the floor by furniture (Bränzel et al., 2013: 725). In this context, Force Sensitive Resistors (FSRs), widely used in smart chair applications, operate by changing their electrical resistance in response to applied pressure and are preferred due to their thin structure and cost-effectiveness (Odesola et al., 2024: 8). Likewise, load cells, typically placed under cushions, convert mechanical force into measurable digital signals (Odesola et al., 2024: 10), while textile-based pressure sensors are developed by integrating conductive yarn patterns into fabric surfaces, offering a flexible and comfortable sensing solution compatible with upholstery (Odesola et al., 2024: 24). Additionally, biomass-derived sensors produced from carbonized materials such as wood, lignin, or rice husks operate based on the piezoresistive effect, detecting resistance changes under mechanical stress and providing a sustainable sensing alternative (Vlaović, 2020: 252).

3.1.2 Interpretation Layer

At the interpretation layer, raw pressure data obtained from the perception layer are processed and translated into meaningful insights regarding the user’s physiological and behavioral conditions. In the literature, pressure sensors are widely used for functions such as classifying sitting postures, detecting incorrect postural alignment, and identifying prolonged inactivity. Accordingly, the interpretation layer represents the cognitive stage in which raw data acquired through pressure sensors are analyzed and transformed into meaningful outputs concerning the user’s physical condition, behavior, and physiological characteristics.In this context, studies have been conducted on the development of measurement protocols and analytical techniques for evaluating pressure distribution in office chairs (Reed & Grant, 1993). Through such analytical processes, sensor-derived data can be interpreted to obtain meaningful information about the user’s sitting posture and body condition. These systems can also provide corrective feedback when improper posture is detected, thereby contributing to the prevention of musculoskeletal disorders.

The interpretation of pressure sensor data also includes the analysis of body weight distribution and movement patterns. By evaluating weight distribution, sensor systems can detect incorrect postures and provide feedback to the user—such as haptic alerts or mobile application notifications-encouraging postural correction (Vlaović et al., 2021: 233). Similarly, smart chair systems have been developed to analyze user mobility and objectively assess the effectiveness of medications for Attention Deficit Hyperactivity Disorder (ADHD) (Wang et al., 2021: 8). This demonstrates that sensor data are not limited to physical measurement but can also generate meaningful outputs for evaluating neurological and behavioral conditions.

At this stage, artificial intelligence–supported data processing and pattern recognition systems enable the development of user-specific interpretation processes by learning individual behavioral patterns. Thus, the interpretation layer of STAM transforms sensor-generated data into meaningful inputs that trigger therapeutic interventions.

The interpretation layer also includes the analytical use of sensor data for ergonomic and design evaluation purposes. In this regard, sensor data can serve as an ergonomic assessment tool for designers, enabling the observation of long-term furniture usage patterns and supporting design optimization (Hong et al., 2001: 262). From this perspective, the

interpretation layer constitutes a critical cognitive process that transforms raw data from the perception layer into meaningful and actionable information related to posture, mobility, physiological state, and behavioral patterns.
Within the STAM framework, these data are not only interpreted as ergonomic parameters but also as indicators of stress, discomfort, and bodily tension. For instance, irregular pressure distribution, frequent posture changes, or prolonged pressure accumulation in specific body regions may indicate not only physical discomfort but also psychological unease experienced by the user.

3.1.3 Therapeutic Intervention Layer

At the therapeutic intervention layer, feedback and physical responses directed toward the user are generated by the furniture based on interpreted data. In the literature, pressure sensors are commonly used in interventions such as posture alerts, pressure redistribution, form transformation, and the control of massage mechanisms.
Within the STAM context, these interventions are realized through haptic feedback, adjustable seating stiffness, and adaptive movements of backrest and support elements. Pressure balancing systems designed for the prevention of pressure ulcers and massage therapy applications enable adaptive furniture to function as a direct bodily relief-oriented therapeutic interface. At this layer, furniture is redefined not as a passive object but as an active system component that continuously interacts with the user and responds to their needs.
The therapeutic intervention layer refers to the stage in which the furniture generates physical, mechanical, or sensory responses based on the interpreted sensor data. In this regard, pressure sensors enable furniture designs to monitor users' sitting habits and physical conditions and to modify their physical form to enhance comfort (Vlaović et al., 2022: 1). In shape-changing smart furniture—such as height-adjustable desks or transformable seating systems—pressure sensors are used to guide mechanical mechanisms and optimize support stiffness according to user load and distribution patterns (Yang & Yang, 2025: 2). These interventions enable furniture to operate as an adaptive system that responds to users' physical characteristics and immediate needs.
This layer also includes physical interventions aimed at preventing health risks. Systems that monitor pressure accumulation on chair or bed surfaces can activate embedded air bladders when excessive pressure is detected, thereby redistributing pressure across the surface (Russell et al., 2017: 1). This mechanism provides a direct physical response to reduce pressure buildup, particularly for individuals with limited mobility. Similarly, AI-supported massage chairs utilize 64-channel pressure mapping technology to identify anatomical regions of the user and customize massage protocols accordingly. These systems dynamically adjust lumbar support and perform mechanical interventions tailored to the user's physical condition (Yang & Yang, 2025: 2).
Furthermore, this layer includes the adaptation of furniture form and structural properties based on sensor data. Pressure sensor outputs can be used to develop morphing furniture designs that automatically adjust their configuration according to users' physical characteristics (Yang & Yang, 2025: 4). In this respect, the therapeutic intervention layer transforms perceived and interpreted data into tangible physical actions, enabling furniture to evolve from a passive object into an active and adaptive system aligned with the user's physiological and biomechanical needs.

3.1.4 Psycho-Physiological Effect Layer (Outcome / Self-Regulation)

The final layer of STAM addresses the psycho-physiological effects of therapeutic interventions on the user. Adaptive furniture designs supported by pressure sensors reduce the load on the musculoskeletal system, thereby enhancing physical comfort while simultaneously strengthening body awareness and supporting self-regulation processes. In the literature, pressure sensor–based systems are associated with indirect psychosocial outcomes such as stress reduction, improved sleep quality, and an increased sense of safety and control. In post-disaster temporary housing environments, such interventions may help mitigate feelings of uncertainty and insecurity, thereby supporting the recovery process. In this context, pressure sensors are not merely technical components but are conceptualized as therapeutic triggers that enable psycho-physiological regulation within the STAM framework.
In the literature on biofeedback and adaptive systems, this layer is defined as the stage that reflects the physiological and psychological effects of interventions carried out after sensing and interpretation processes. The primary aim of biofeedback systems is to monitor physiological processes, provide feedback regarding these processes, and thereby support the regulation of psycho-physiological states such as stress levels, muscle tension, heart rate, and posture (Schmidt & Wrisberg, 2008; Vlaović et al., 2021). In this context, sensor-based feedback and adaptive interventions contribute not only to physiological outcomes—such as reducing musculoskeletal load, promoting muscle relaxation, improving posture, and enhancing overall physical comfort—but also to psychological outcomes, including increased self-awareness, stress reduction, and emotional regulation (Lauber & Keller, 2014; Odesola et al., 2024).
Within the context of smart furniture and biofeedback systems, the psycho-physiological effect layer encompasses the outcomes of adaptive physical interventions based on sensor data in relation to user health, comfort, and behavior. Studies have demonstrated that systems developed using pressure sensors and similar sensing technologies contribute to correcting poor posture, preventing musculoskeletal disorders, and reducing muscle tension, thereby enhancing physical relaxation (Russell et al., 2017; Yang & Yang, 2025). Moreover, these systems enable early detection of health risks through the monitoring of vital physiological parameters such as heart rate and respiration, and contribute to supporting independent living, particularly among elderly users (Zhang et al., 2021; Lim et al., 2008). In this respect, the psycho-physiological effect layer represents the outcome of the perception, interpretation, and therapeutic intervention processes within the STAM model, revealing the holistic impact of the system on user health, comfort, and psychological well-being.

Table 1: Pressure sensor–based adaptive furniture process and therapeutic effects.

Pressure Sensor Data	Data Interpretation	Furniture Response	Therapeutic Effect on the User
Seating pressure and weight distribution	Posture analysis and detection of postural disorders	Readjustment of the seating surface and optimization of back support	Increased postural awareness and reduced musculoskeletal load
Localized high pressure areas	Pressure accumulation and circulation risk analysis	Pressure redistribution (air bladders, surface adaptation)	Prevention of pressure ulcers and physical comfort
Prolonged inactivity	Detection of inactivity and prolonged sitting duration	User alerts (vibration, notification) or movement encouragement	Improved circulation and reduced health risks
Micro movements and vibrations	Extraction of physiological data such as respiration and heart rate	Adjustment of the environment or seating comfort	Reduced stress and increased physiological awareness
Usage duration and sitting habits	Behavioral pattern analysis	Application of personalized settings	Increased comfort and improved user experience

3.2 Adaptive Furniture Design Based on Force Sensors

3.2.1 Perception of the User

Within STAM's perception layer, force sensors are positioned as components that measure the total mechanical load, weight, and resistance applied not to the surface of the furniture but to its structural frame, mechanisms, or specific contact points. As reported in the literature, load cells, force-sensitive resistors (FSRs), and piezoelectric sensors are integrated into furniture structures to address different force measurement requirements.

Load cells are typically placed within the furniture frame or beneath seating surfaces, enabling continuous monitoring of the user's net weight and shifts in the center of pressure. FSR sensors, on the other hand, are integrated into narrow areas such as backrests or armrests to detect leaning behavior and the magnitude of applied force. Piezoelectric and smart sensors are used in moving components to detect vibrations or load variations on motors, particularly in collision prevention systems. In this context, force sensors are regarded as fundamental sensing components at the perception layer, generating macro-scale data related to the mechanical state of the furniture and user–furniture interaction.

The perception layer refers to the stage in which mechanical load, weight, resistance, and movement-related force data generated during user interaction with furniture are physically measured through force sensors. In this regard, force sensors are critical components used not only to measure surface pressure but also to capture mechanical loads applied to the structural frame, mechanisms, or specific contact points of furniture.

Accordingly, load cells are generally embedded in the furniture frame or beneath seating surfaces, and for instance, four load cells placed under an office chair can continuously monitor the user's net weight and shifts in the center of gravity. Force-sensitive resistors (FSRs) are passive polymer films that change their electrical resistance according to the applied force, and due to their thin and compact structure, they can be integrated into narrow areas such as backrests or armrests, reporting leaning behavior and force magnitude as analog values. Piezoelectric and smart sensors, meanwhile, provide data related to the mechanical state of the system by detecting vibrations in moving components or load variations on motors (Yoshida et al., 2023: 3).

Force sensors also play an important role in capturing data related to the user's physical condition. Continuous data streams from load cells can monitor weight distribution and movement patterns, and enable the detection of prolonged inactivity (Abdullah et al., 2025: 23). Similarly, in lift-assist chairs, force sensors detect load variations on motors and obstacle conditions, providing data related to the system's mechanical state (Maňak, 2014: 1026). In this respect, the perception layer ensures the continuous measurement of force, resistance, and weight data generated during user interaction with furniture, forming the fundamental input for subsequent system processes.

3.2.2 Interpretation Layer

At the interpretation layer, force data obtained from the perception layer are processed and translated into meaningful insights regarding user behavior, movement patterns, and interaction modes with furniture. The primary distinction between force sensors and pressure sensors lies in their focus on total mechanical load and resistance values rather than distribution per unit area. Accordingly, force sensor data enable the detection of conditions such as weight transfer, prolonged inactivity, applied force levels on furniture, and uneven loading patterns. When used in combination with pressure mats, these data also allow for the differentiation between ergonomic assessment and conditions requiring mechanical response. Within the STAM framework, the interpretation layer considers force sensor data not merely as numerical measurements but as indicators of safety, mobility limitations, and support requirements.

The interpretation layer refers to the stage in which raw data obtained from force sensors are analyzed and transformed into meaningful information regarding the user's physical condition, movement behavior, and interaction with furniture. In this context, continuous data streams from load cells enable the detection of prolonged inactivity, thereby allowing the system to identify specific behavioral states (Abdullah et al., 2025: 23). This analytical process facilitates the transformation of force sensor data into meaningful behavioral inferences about the user.

Similarly, in mechatronic furniture designs, force sensor data can be used to adjust the support force provided by a chair according to the user's muscle strength, enabling the system to operate in accordance with the user's physical capacity (Maňak, 2014: 1028). This process demonstrates that force sensor data are not only used for measurement purposes but also constitute a foundational input for system decision-making processes.

The interpretation of force sensor data also involves technical data processing procedures. The integration of force sensors into furniture design requires the use of microcontrollers (e.g., ESP32, Arduino) and data processing algorithms to handle sensor outputs (Abdullah et al., 2025: 21). In addition, accurate calibration processes are essential to ensure consistent and reliable results from load cells under varying weight distributions (Zemp et al., 2016: 2). In this respect, the interpretation layer enables the transformation of perceived force data into meaningful and actionable information through systematic processing.

3.2.3 Therapeutic Intervention Layer

At the therapeutic intervention layer, physical and kinesthetic responses are generated by the furniture based on interpreted force data. In the literature, force sensors are not only considered as input devices but also as output (feedback) mechanisms. In this context, resistance modulation emerges as a prominent application in interactive chair design. Dynamically adjusting the resistance applied to user actions such as rotating, reclining, or sliding the chair creates a kinesthetic form of feedback perceived through the user's muscles and joints. In scenarios where force is used as a communication medium, interventions such as intentionally increasing the resistance of chair backrest recline movements provide haptic information to the user. In addition, force sensors are also used in applications such as adjusting motor power in lift-assist chairs, stopping movement when an obstacle is detected, and optimizing support force in mechatronic systems according to the user's muscle strength.

The therapeutic intervention layer refers to the stage in which the furniture generates physical and mechanical responses based on interpreted force data. In this context, force sensors enable the adaptive adjustment of mechanical systems in accordance with user needs. For instance, in lift-assist chairs, force data are used not only to regulate motor lifting power but also to stop movement when an obstacle is detected in order to prevent entrapment (Maňak, 2014: 1026). This intervention enables the system to produce a direct physical response aimed at ensuring user safety.

Force sensors are also used to generate direct physical interaction through resistance modulation. In designs such as "Aarnio," for example, the resistance applied to user actions such as rotating, reclining, or sliding the chair is dynamically modulated, creating a kinesthetic feedback perceived through the user's muscles and joints (Teng et al., 2019: 672). Similarly, increasing resistance by deliberately making backrest recline more difficult establishes a form of haptic communication that allows users to receive information without using their hands (Teng et al., 2019: 672).

Force-controlled interactions are also employed in virtual reality and simulation environments to produce therapeutic and interactive interventions. In this context, applications such as locking the rotational force of a seat in the event of vehicle damage or increasing backrest tension during acceleration enable physical responses based on force sensor data (Teng et al., 2019: 672). Furthermore, force sensor data allow the system to adapt to the user's physical condition by adjusting support force in accordance with muscle strength (Maňak, 2014: 1028).

3.2.4 Psycho-Physiological Effect Layer

At the psycho-physiological effect layer of STAM, the indirect therapeutic outcomes of interventions enabled by force sensors are addressed. Reminders for "standing up" triggered by force sensor data contribute to the prevention of prolonged inactivity, while controlled assistance in lift-support chairs creates safe usage conditions for elderly and mobility-impaired users. In addition, adjusting support force according to the user's muscle strength helps prevent complete muscular inactivity, thereby contributing to the management of muscle weakness. This demonstrates that, within the STAM framework, force sensors play a role not only in safety and ergonomics but also in supporting bodily regulation processes.

The psycho-physiological effect layer refers to the impacts of physical interventions based on force sensor data on user health, safety, and physical condition. In this context, force sensor data enable the detection of prolonged inactivity, thereby allowing the system to trigger "stand-up" reminders (Abdullah et al., 2025: 23). This contributes to reducing health risks associated with long-term sedentary behavior.

Similarly, in lift-assist chairs, the use of force sensors ensures safe user support and enhances physical safety by stopping movement when an obstacle is detected (Maňak, 2014: 1026). Moreover, adjusting the support force according to the user's muscle strength prevents complete muscular inactivity and contributes to the management of muscle weakness (Maňak, 2014: 1028). In this respect, the psycho-physiological effect layer represents the outcomes of adaptive interventions enabled by force sensors in terms of user health, safety, and musculoskeletal function.

The processes of perception, interpretation, transformation into adaptive intervention, and psycho-physiological effects derived from force sensor data are presented as an integrated framework in Table 2.

Table 1: Force sensor–based adaptive furniture process and therapeutic effects.

Force Sensor Data	Data Interpretation	Furniture Response	Therapeutic Effect on the User
Total body weight and center of gravity shift	User position analysis and movement state detection	Seating support adjustment, balance optimization	Posture control, ergonomic awareness, safe sitting
Prolonged static load (inactivity)	Inactivity and prolonged sitting risk analysis	Standing reminder or movement encouragement	Circulation support and reduction of inactivity-related risks
Uneven force distribution	Ergonomic loading and support requirement analysis	Adjustment of support stiffness or seating position	Reduction of musculoskeletal load and increased physical comfort

Mechanical resistance and applied force	User interaction force and behavioral analysis	Resistance movement adjustment	modulation, resistance/assistance	Kinesthetic awareness and support of muscle activation
Motor yük değişimi ve sistem direnci	Mechatronic system status and safety analysis	Movement adjustment	stopping or speed	Sense of safety and reduction of physical risks

4. Discussion

In the literature, the primary objective of biofeedback systems is defined as enhancing an individual's self-regulation capacity by monitoring physiological processes in real time (Schmidt & Wrisberg, 2008; Giggins et al., 2013). The findings of this study suggest that a similar mechanism can be transferred to the interior scale. In particular, the continuous integration of data obtained from pressure and force sensors into a feedback loop transforms user–furniture interaction from passive ergonomic optimization into an active behavioral learning process.

This corresponds to the fundamental principle of closed-loop biofeedback systems. Kos and Umek (2018) define biofeedback as a cyclical control mechanism that enables continuous adaptation through the processing of sensor data and feedback delivery to the user. Similarly, Giggins et al. (2013) demonstrate that such systems are effective in motor learning, posture control, and rehabilitation processes. In this context, adaptive furniture designs can also be considered to generate a comparable learning and adaptation mechanism.

In terms of therapeutic outcomes, the findings indicate a three-level effect structure: physical, behavioral, and psychological. At the physical level, effects such as postural correction, load distribution optimization, and reduction of prolonged inactivity play a critical role in preventing musculoskeletal disorders (Lauber & Keller, 2014; Odesola et al., 2024). At the behavioral level, the reshaping of users' sitting and movement habits through system feedback aligns with the literature on motor learning and habit formation (Shadmehr & Krakauer, 2008). At the psychological level, outcomes such as increased sense of safety, stress reduction, and enhanced bodily awareness correspond to the psychosocial effects of biofeedback-based interventions (Schmidt & Wrisberg, 2008; Petr et al., 2022).

On the other hand, the integration of such systems into interior environments also raises several design and ethical discussions. Continuous data collection and monitoring of user behavior bring issues such as privacy, data security, and user control to the forefront. Furthermore, the capacity of adaptive systems to influence user behavior reopens the debate on whether design should be directive or supportive. The ability to embed sensors in concealed or invisible locations within furniture makes their use as interface elements particularly advantageous in residential smart product design, where aesthetics and spatial experience are critical (Yoshida, 2022).

5. Conclusions

This study explored the potential of sensor-based adaptive furniture designs to support therapeutic outcomes and examined how such outcomes may differ according to sensor type. Through a thematic analysis of pressure and force sensors within the proposed Sensor-Based Therapeutic Adaptation Model (STAM), the findings suggest that adaptive furniture can be conceptualized as a therapeutic environmental interface capable of supporting psycho-physiological regulation through biofeedback-inspired interaction mechanisms.

Regarding the first research objective, the study demonstrates that the perception–interpretation–response cycle central to biofeedback systems can be meaningfully translated into the context of adaptive furniture design. The four-layer structure of STAM -comprising perception, interpretation, therapeutic response, and psycho-physiological outcome layers- provides a conceptual framework through which furniture can be understood not as a passive object but as an active environmental mediator. In this respect, adaptive furniture may facilitate continuous interaction between user states and environmental responses, thereby supporting self-regulation processes.

Concerning the second research objective, the findings indicate that different sensor types may contribute to distinct dimensions of therapeutic experience. Pressure sensors appear particularly relevant for posture awareness, pressure redistribution, and musculoskeletal support, whereas force sensors are associated with physical comfort, kinesthetic awareness, movement assistance, and safety-related functions. These differences suggest that therapeutic potential is not inherent to adaptive furniture itself but emerges through the specific sensing and response mechanisms embedded within the system.

With regard to the third research objective, the analysis identified a three-level outcome structure consisting of physical, behavioral, and psychological dimensions. Physical outcomes include posture support, load redistribution, and reduction of prolonged inactivity. Behavioral outcomes relate to increased awareness of sitting and movement habits, while psychological outcomes may include enhanced feelings of safety, bodily awareness, and environmental support. Collectively, these findings suggest that adaptive furniture designs have the potential to extend the discourse on therapeutic interiors beyond conventional ergonomic considerations toward broader questions of well-being and self-regulation.

The study contributes to the literature in three principal ways. First, it identifies a conceptual gap at the intersection of biofeedback systems, adaptive furniture, and therapeutic interior design. Second, it introduces the Sensor-Based Therapeutic Adaptation Model (STAM) as a theoretical framework that translates biofeedback principles into the context of interior architecture and furniture design. Third, it proposes a structured analytical approach for examining how different sensor technologies may be associated with different therapeutic outcomes, thereby providing a foundation for future investigations into sensor-based therapeutic environments.

From a practical perspective, STAM offers interior architects and designers a conceptual framework for integrating sensor technologies into user-centered and health-supportive environments. The model provides a systematic vocabulary for evaluating how sensing, interpretation, and adaptive response mechanisms may be employed to address specific psycho-

physiological needs. For researchers, the model establishes a basis for future empirical studies involving prototype development, user testing, physiological measurements, and longitudinal evaluations of adaptive furniture design.
In conclusion, this study suggests that sensor-based adaptive furniture designs may represent an emerging design paradigm within therapeutic interior environments. By integrating sensing technologies, biofeedback principles, and adaptive responses, furniture can be reconceptualized as an interactive environmental interface that supports user well-being through continuous and responsive interaction. In this regard, STAM provides a theoretical foundation for future research at the intersection of interior architecture, human-centered technology, and therapeutic design.

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