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A transdisciplinary approach to model user-product interaction: how the collaboration between human sciences and engineering design could improve product development for physically impaired people

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Abstract. Product design for people that suffer from physical impairments is a challenging task since design engineers usually lack the human specific knowledge necessary to address particular requirements of these user groups. In fact human-centred design is a problem area between engineering and human sciences. This contribution proposes biomechanical modeling as a transdisciplinary approach in human-centred design. Based on a neurological hypothesis a simulation procedure is developed that can help designers to adjust their solutions to the actual capabilities of the users.

Keywords: human-centred design, computer aided design, biomechanics

1 Introduction

Due to an increasing expectancy of life and a declining birth rate many industrialized countries are facing the phenomenon of demographic ageing. As a consequence elderly people represent a growing proportion of the population. The process of ageing however is accompanied by a change in many of the cognitive and physical abilities. Especially motor performance is likely to get worse. Even though this is a natural process, an accumulation of physical impairments within the population has to be anticipated. In view of this the importance of products that help to maintain the users' quality of life will grow further. Typical examples are assistive technology products that restore or compensate the users` loss of ability. But also items of everyday life like e.g. bicycles have to be designed to fulfill the needs of people with physical impairments. To industry the impact of demographic ageing becomes even more relevant as the distribution of wealth shifts more and more to the side of elderly customers.

A major issue within the development of products for physically impaired users is that this user group is characterized by a high heterogeneity of their capabilities and needs. Therefore the design process should follow the paradigm of human-centred design, which is explained in the following section.

2 Human Centred Design – a chance for transdisciplinarity

Human-centred design is a design paradigm that aims at creating products perfectly tailored to the actual needs and abilities of a certain user group. This is achieved by a holistic view on the system formed by the user and the product (Fig. 1). It is assumed that the product is described by a set of technical, economical and human-related properties. The user as a human being on the other side is characterized by demographic (e.g. age, gender, constitution) and psychographic (e.g. attitude, lifestyle) properties. The interaction between user and product is modeled as a process of perception and response. Based on perception and recognition the user is able to assess the properties of the product and choose an adequate behavior. Most important the behavior includes all activities necessary to operate the product. [1] It is up to the designer to adjust the properties of the product so that the interaction processes become optimal with respect to some performance criteria. Possible criteria are safety, harmlessness, usability and user experience. In this context safety means that the immediate risk of e.g. injuries should be minimized during the use of the product while harmlessness addresses the long-term effects on the users´ health and constitution. Usability means the effectiveness and satisfaction to which the user can accomplish the purpose of the product. The term user experience stands for all the emotional aspects like e.g. the fun of driving a sportive car or the pride the owner of an expensive smart phone may feel.

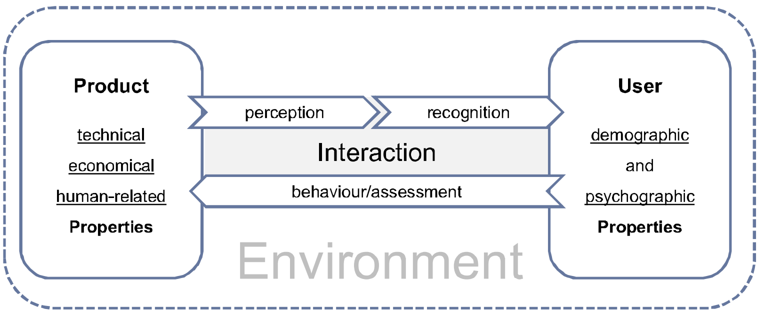

Fig. 1. User-Product relationship according to [1]

In praxis however it might be unclear how the analysis and optimization of interaction processes can be accomplished. For design engineers a major challenge might be that user-product interaction cannot be benchmarked by only using technical measures since the performance criteria mentioned above are human-related and require a deeper understanding of body and mind. Designers have to consider *biomechanical*, *physiological* and *psychological* aspects in addition to technical and economic constraints. Now it becomes evident that human-centred design is not an isolated idea within design but can only be successful in collaboration with other disciplines. The question is how this collaboration is organized. Transdisciplinarity is often suggested to find solutions for problems that exceed the boundaries of a single scientific discipline. However while there seems to be no homogeneous definition of transdisciplinary research our understanding is influenced by the work of Wickson et al. [2] who examined three main characteristics within a literature survey: *problem orientation*, *fusion of methodologies* and *stakeholder participation*. Transdisciplinary research focuses on complex, multidimensional real world problems that need to be solved and not only put into a conceptual construct of ideas. The collaborating disciplines share a common vision and contribute their expertise but do not insist on their specific methodologies and epistemologies. Ideally they fuse their heritage into new research methods that respond to the actual problem. An important aspect of transdisciplinarity in research is further the collaboration between researchers and the broader community of people who are affected by research. Ideally there is a participation of stakeholders to ensure that all research activities remain relevant to reality. In the following it will become evident that established approaches towards human-centred design like expert evaluations and usability tests adopt some of these transdisciplinary ideas.

The method of expert evaluation requires a team of engineers, ergonomists, psychologists and orthopaedic specialists. This team will try to identify possible problems in the user-product interaction process with the goal to provide recommendations for design improvements. [4] Even though this collaboration is characterized by a common vision there is no fusion of methodologies or scientific findings. The particular disciplines merely contribute to the solution of a purely design related problem. Since experts are usually not a part of the user group the quality of their work depends heavily on how they can put themself into the position of the user. This issue is addressed by methods of direct user integration. Usability tests are commonly applied to evaluate an existing design concept with the help of test persons that represent the target user group. Thereby a prototype of the product is presented to test persons. Interview and observation of these persons can lead to substantial design improvements. [3] In order to reduce the costs for the manufacturing of functional product prototypes digital alternatives [5], [6] were developed that make it possible to conduct usability tests in Virtual Reality environments. Processes of direct user integration implement the idea of stakeholder participation.

Finally multidisciplinary expert committees developed guidelines like VDI 2242 [7] or ISO 9241-210 [8] that should assist design engineers in decision making. It is important to notice that due to the heterogeneity and complexity of human characteristics and the huge amount of imaginable products every design case is unique. Thus it is not possible to formulate universal design rules. Instead guidelines can only give a rough advice in which direction to think and which scientific fields to consult further.

Since product design is always focused on real world problems it is predestined to accommodate transdisciplinary research. However even though human-centred design lives on the collaboration of multiple disciplines and contains some transdisciplinary elements all activities mentioned above are initiated from an engineering point of view. In particular the benefit for the human sciences involved is weak.

In this contribution digital biomechanical simulations are proposed as a method to evaluate the biomechanical aspects of user-product interaction. The advantage of this approach over traditional ergonomic tests is that the examination can be done entirely in a virtual environment. This leads to a reduction of costs and gives designers much more freedom to think through multiple concepts. In the following section we will give a short introduction to biomechanical modeling and expose that this is a transdisciplinary research area involving mechanical engineering, anatomy, control system theory and neurology. Another important aspect is the consideration of the physical impairments within the simulation based on findings made by gerontologists.

3 Biomechanical modeling to evaluate user-product interaction

3.1 Fundamentals of biomechanical simulation

The field of biomechanics addresses structure and motion of human and animal musculoskeletal systems. This comprises the mechanical behavior of bones, joints and muscles as well as the complex sensorimotor processes that control the motion of the entire system. Biomechanical simulation tools like *OpenSim* [9] and *Anybody* [10] have been developed to describe the behavior of biomechanical systems based on multibody dynamics. The skeleton is modeled as a set of rigid bodies that are interconnected by joints whereas muscles are represented by special force actuators that take into account the physiological contraction-force relationship.

In product design biomechanical simulations offer a unique opportunity to evaluate the interaction between users and products with respect to ergonomic aspects. The basic idea is to use simulated body-internal load quantities such as joint torques, mechanical work or muscular activity as indices for the performance of the interaction process. In this context the research of Rasmussen et al. [10] can be regarded as pioneer work: biomechanical human models were used to find optimal designs of consumer products like e.g. a hand saw and a car seat.

In order to model processes of user-product interaction human body poses and motion sequences need to be predicted using a forward dynamic simulation approach. Muscles are activated by neural signals generated by the central nervous system (CNS), which means that in order to predict coordinated human movement neurological control processes have to be considered as well within the model. This is the thematic connection between design and the field of neurological research on human motor coordination where simulations of biomechanical systems are used to prove or disprove scientific hypotheses. Applications in design rely on technical implementations of motor control hypotheses to predict human behavior during the interaction with products. Therefore common hypotheses are presented in the following section. It is important to notice that this collaboration between engineers and neurologists can be regarded truly transdisciplinary since there is a common vision (understand motor coordination) and the results are used to solve a real world problem. Since customers buy the products that were developed based on neurological findings, neurologists benefit from having stakeholders integrated in their research.

3.2 Hypotheses of motor control and technical implementation

The Greek philosopher Aristotle was one of the first scientists to investigate coordinated movement of animals and human beings. He described coordination as an interaction process between the environment and the creature´s soul. According to this idea the soul plays the role of a controller that initiates movements of the body subject to environmental influences. Since the beginning of the 20^{th} century when motor control came into focus of modern sciences, several theories were developed and refined that tried to unveil the physiological and neurological mechanisms behind coordinated movement. In all modern theories without doubt the Central Nervous System (CNS) is identified as the controlling instance. In some ways the CNS equates to what Aristotle called the soul. Despite this agreement two apparently contradictory basic hypotheses emerged in the research of motor control. The reactive hypothesis argues that biological movement always appears as a response to signals from the environment. A representative of this hypothesis was developed by the Russian physiologist Pavlov. Pavlov assumed that human behaviour is governed by reflexes. A reflex can be seen as an inborn or conditioned connection between an external stimulus and a response. Coordinated movements are combinations of basic reflexes that are stored in the CNS. [11] In contrast to this the active hypothesis considers movements as predefined actions that are initiated by will. Bernstein [12] came up with the idea of motor programs stored in the CNS memory. These so-called engrams are pre-planned time functions of abstract variables that encode the characteristics of motion sequences. Of course there are also theories that combine both active and reactive elements. One example is the Equilibrium Point Hypothesis (EPH) developed by Feldman [13]. Since the EPH is conform to phenomena that can be observed in experiments, it is accepted by many scientists. Especially the experiments on monkeys conducted by Polit and Bizzi [14] encourage the EPH. The central idea of the EPH is that reflexes are not hard wired but contain parameters that can be modulated by the CNS through motor programs. In this way Feldman adopted elements of Pavlov and Bernstein. In Fig.2 this idea is illustrated under a simplified point of view. Muscles contain contractile elements that can be activated by neural signals coming from the CNS. As a consequence the muscle contracts while a force is generated. At the same time muscles are also equipped with sensory organs (spindle organs) so that the CNS is aware of the muscle´s current length l and its contraction velocity v. Stretch reflexes such as the well-known knee-jerk reflex are triggered around a threshold λ. This threshold can be identified as a set-point for the length of the muscle. As long as the actual length l is smaller or equals λ the muscle remains in rest. As soon as the muscle is stretched e.g. by an external force F so that l becomes bigger than λ it is activated by the CNS. The level of activation increases with the deviation of l with respect to λ. This mechanism assures that the muscle and the limb it is connected to always move into an equilibrium position depending on λ and the external forces F. According to the EPH the CNS is able to generate coordinated movement by modulating λ for every muscle in the body. Thus motor programs describing motion sequences resemble time functions of λ-values. The actual muscle forces necessary to accomplish the motion sequence are automatically regulated by the stretch reflexes in accordance with the external conditions.

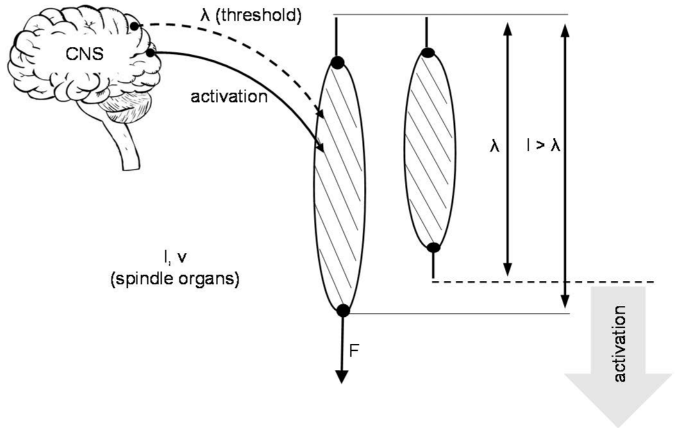

Fig. 2. Equilibrium Point Hypothesis on motor control (EPH)

Because of its vicinity to control system theory a technical implementation of the Equilibrium Point Hypothesis is straightforward. In the following a biomechanical simulation procedure based on EPH is presented that can be used to evaluate user-product interactions. Our implementation (Fig.3) is currently based on a simplified biomechanical model of the human body. Instead of muscles idealized torque actuators are used to drive the skeleton. A motor program then comprises time series of set-point joint angle vectors that resemble body poses. Hence the λ commands define a kinematic configuration of the skeleton. They do not encode any dynamic quantities. The motor program is generated by an inverse kinematic solver, which transforms a task description into a series of body poses by employing numerical optimization. In this way it acts as the planning instances located in the CNS. In the task description the purpose of the motion has to be encoded using a high level concept of geometrical constraints and objectives. In the present example the process of a person getting up from a chair was chosen as a task. Here two constraints are used to keep the feet on the ground. The actual movement originates from an objective that assures that the body is always balanced while the knees and lumbar joints are getting stretched. The series of joint angle vectors are passed on to the forward dynamic simulation model. Within this model the stretch reflexes are represented by a simple PD control mechanism: activation signals for the torque actuators are computed proportional to the difference between the actual joint angle value and the current λ set-point value. In addition the angular velocity of each joint in the body is used for damping. The control gains GP and GV have to be adjusted by trial and error but it can be expected that in a biological system the CNS will modulate this parameters to alter the stiffness of the musculoskeletal system. As a result of the dynamic simulation internal load quantities like e.g. the history of activation signals or the mechanical work are available and can be used as performance indices to assess the motion sequence. If the task describes a user-product interaction process these indices can be interpreted as measures for the ergonomic quality of the design concept.

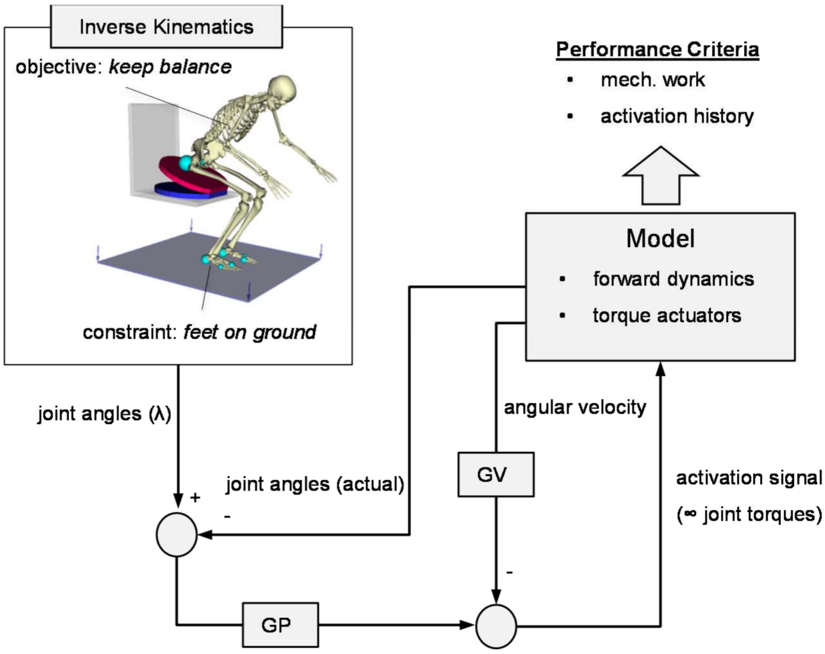

Fig. 3. Simulation procedure based on EPH

3.3 Human models with performance restrictions

The informational value of biomechanical simulations depends on if the model represents all the human characteristics that are expected to influence the behavior of the user. Since the potentials of human-centred design arise especially in the development of products for physically impaired and elderly people, ways have to be found to consider these performance restrictions within the model. This is only achievable in collaboration of design engineers, medical scientists and gerontologists. Within the transdisciplinary research project *Fit4Age* [15] three main categories of ageing related performance restrictions and have been identified: Sensory Capabilities: In this category especially visual and auditory abilities change over the life span. For example the sharpness and contrast of the visual system decrease (presbyopia) either due to the deteriorating accommodative capacity or to pathological conditions like macular degeneration and cataract. Motor Skills: This umbrella term subsumes strength, endurance, speed of motion, coordination and mobility. As ageing progresses reaction times increase and the precision of movements decreases. Common diseases like Parkinson or Arthritis restrict the mobility even further. Arthritis e.g. is accompanied with the deterioration of the range of motion due to the wear of joints and pain while moving. Cognitive Abilities: Cognitive faculties can be subdivided into mechanical and pragmatic capabilities of the human mind. Mechanical faculties are abilities needed in unknown or fast changing situations like processing speed, capacity of the working memory, attention and spatial orientation. These capabilities are negatively correlated to age and highly heterogeneous inside the age groups. The pragmatic faculties are defined by the knowledge of a person acquired throughout life and therefore enhance with age. Cognitive disorders like dementia, depression and delirium generally affect the cognitive abilities negatively. Since all these items are relevant for planning and execution of biological movement they need to be considered in the development of biomechanical models with performance restrictions. For this purpose we are currently initiating a research network composed of designers, experts from medical sports science, psychologists and gerontologists. However our current simulation procedure does not consider any performance restrictions yet but it is crucial to implement these in future work.

4 Case Study: design of a bicycle frame

4.1 Objective

In the following our simulation procedure shall be further illustrated in a case study. The product to be designed is a frame intended for a comfortable touring bicycle. It is not the objective of this project to go through a complete human-centred design process. Instead it shall be demonstrated how geometrical changes in the product design effect the performance of the interaction process with the user and how these effects can be revealed by a biomechanical simulation. Therefore it is sufficient to consider only a single geometrical dimension of the frame depicted in Fig.4. It is expected that the distance d1 between the bottom bracket and the position of the saddle mount has got a great impact on the performance of the entire system comprising the bicycle and the rider. To prove this several simulations of biomechanical human model riding a virtual prototype of the bicycle are performed while d1 is varied. Afterwards the internal dynamic quantities of the user´s body are analysed.

4.2 Model

The simulation procedure was implemented on top of *OpenSim* [9] a biomechanical simulation environment that is being developed at Stanford University by a team mainly occupied in medical rehabilitation research. Fig.4 shows the model used within this case study. The user is represented by a skeleton featuring 30 degrees of freedom which means that only the major joints of the human body were considered. The skeleton resembles a male subject with a body height of 1.74 m and a body mass of 71 Kg. Further the skeleton is driven by idealized torque actuators allocated directly to the joints. This simplification had to be made because our implementation of the EPH currently does not work on muscle actuators. The geometry of the bicycle frame is modeled indirectly by specifying the spatial positions of where the hands get in touch with the handle bar and where the buttocks rest on the saddle. Therefore a set of geometrical constraints is used. Moreover the feet are constrained to remain on the pedals. At the inverse kinematic stage of the simulation an objective has been defined that balances the center of gravity (COG) of the skeleton to remain close to the xy-plane (sagittal plane). Finally to mimic the power required to drive the bicycle, a constant torque of 5 Nm is applied to the crank that rotates at a frequency of 60 rpm. Consequently the user has to produce a constant power of 31W.

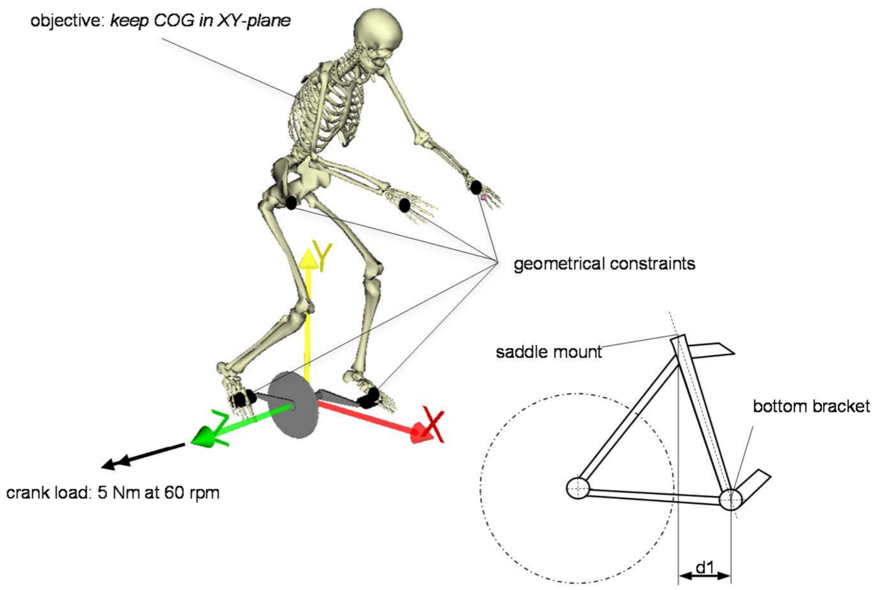

Fig. 4. Simulation model

4.3 Results and Discussion

In total three simulation runs were performed with different values for the dimension d1 so that the saddle mount was successively moved backwards from the bottom bracket. As a performance index for the interaction process of riding the bicycle the sum of the mechanical work done by all torque actuators in the body was determined. The results are depicted in Fig.5. It is obvious that the total work declines the further the saddle mount is moved backwards. Also the peaks occurring near the dead centers of the crank (around t=0.5 s and t=1 s) are remarkable lower if the saddle is moved further away from the bottom bracket.

These results demonstrate how biomechanical simulations can be used to analyze the effect that geometrical changes in the product design can have on the performance of the interaction process with the user.

However it has to be mentioned that the simulation procedure has not been validated yet. The validation is currently being worked on in collaboration with sports scientists who contribute their profound knowledge on human biomechanics as well as the equipment necessary to conduct experiments involving real test persons. In the concrete case of the bicycle frame, the motion of a test person riding an ergometer featuring a frame with mutable geometry is recorded. Subsequently a kinematic comparison of the motion sequences reveals possible deviations with respect to our virtual simulation approach.

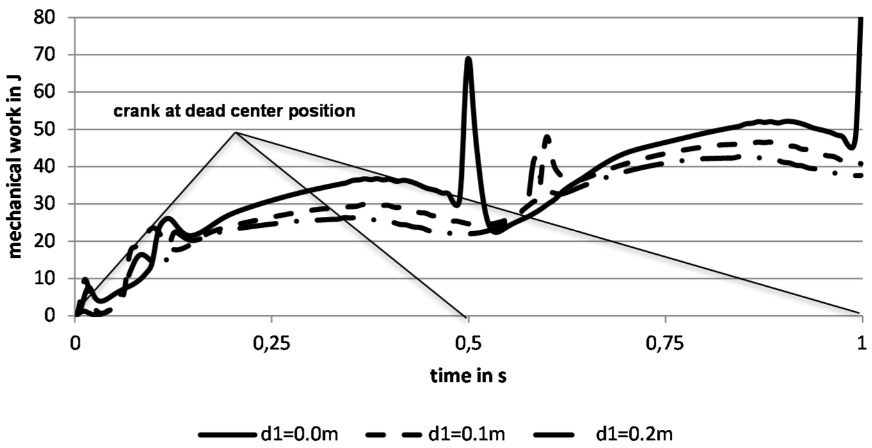

Fig. 5. Sum of mechanical work

5 Conclusion and Outlook

In future the importance of products tailored to the actual needs and capabilities of people suffering from physical impairments will grow without doubt. Human-centered design can help to achieve this requirement. In this contribution it has been pointed out that this design paradigm can only be applied successfully in collaboration with human scientists since designers usually lack the specialized knowledge necessary to keep track of the inseparable system formed by the product and its user. This research can be understood as a transdisciplinary process since human-centred design shares some visions with classic human sciences. Promising examples are the research in human motor control whose hypotheses are applied to predict human behavior during user-product interaction processes as well as the examination of human performance restrictions and their influence on the interaction processes.

The biomechanical simulation approach presented in this contribution is neither complete nor suitable for an application in industry. Future work will focus on the implementation of performance restrictions and the design of a validation process. Nevertheless this example reveals an idea of how product design - especially for people that suffer from physical impairments – can look like in the future. It is obvious that this goal can only be reached in broad collaboration with other scientific disciplines. Ideally within a transdisciplinary framework.

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