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The interplay between perception and action in interpersonal haptic light touch interactions for balance support

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List of abbrevations

ACC	Accident Compensation Cooperation
ADL	Activity of daily living
AP	Anteroposterior
AS	Active Support
BOS	Base of support
CNS	Central nervous system
COM	Center of Mass
COP	Center of Pressure
CP	Contact Provider
CR	Contact Receiver
EMMS	Estimated Marginal Means
fMRI	Functional Magnetic Resonance Imaging
FR	Functional reach
GRF	Ground reaction force
GT	Guided training
HRI	Human Robot Interaction
ICF	International Classification of Functioning, Disability and Health
ICIDH	International Classification of Impairment, Disability and Handicap
IMC	Interpersonal motor coordination
IMS	Individual motor signature
IPC	Interpersonal coordination
IPT	Interpersonal touch
LT	Light touch
MFR	Maximum forward reach
ML	Mediolateral
MPF	Mean power frequency
MRI	Magnetic Resonance Imaging

MTP	Mean total power
NMSS	Neuro-musculoskeletal system
OBT	Object target
PAC	Perception action coupling
PP	Predictive processing
PS	Passive Support
PT	Physiotherapist
RMS	Root Mean Square
ROLITOS	Robotic light touch support
RT	Robot touch
SAD	Social anxiety disorder
SOT	Sensory Organization Test
TGBS	Tinetti Gait and Balance Score
VIC	Visuotactile interpersonal context
VOR	Vestibulo ocular reflex

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Devotement

For Mom and Dad

I would be nothing without you.

You equipmed me with the right tools and values

to withstand many a time storms

that pass by during the journey of life.

I would have never managed this PhD ride without your love and encouragement.

English dissertation title

The interplay between perception and action in interpersonal haptic light touch interactions for balance support

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1 Summary

Caregiver-patient interaction relies on implicit or explicit forms of interpersonal coordination, for example, during manual support when a therapist supports a patient with balance insecurities. Thus haptic support during an interaction between two individuals can be seen as an ecologically well grounded and efficient approach for supervising a patient's risk for falling in challenging balance situations.

However, from the perspective of a therapist, reducing the movement degrees of freedom of the patient by holding the body to help stabilizing the control of balance of the patient seems to be rather counterproductive as it inhibits the patient from exercising own control of body balance.

However an auspicious strategy in order to find the trade-off between patient safety and motor recovery could be a light touch to support postural control. A light touch on the arm of a subject could be one example from a clinical setting.

During this haptic contact, we assume that coordination of movement between therapist and patient occurs. How interpersonal interactions for haptic guidance are actually implemented in balance rehabilitation remains unknown to the best of our knowledge. Although clinical guidelines and patient handling manuals provide descriptive models for caregiver behaviour in routine clinical situations, such as physical support, empirical evidence for the efficacy and superiority of these behavioral models remains scarce. Hence, this work intends to study interpersonal haptic coordination for balance support.

This work aims to enhance the knowledge about the dynamics of interpersonal light tactile support for balance control in general and the interactions between therapists and balance impaired humans for balance stabilization in particular. In doing so, the author aims to provide substantation of new methods to be used for balance rehabilitation in clinical settings.

The present work aims to add more knowledge about the possible stabilizing effects when using light haptic cues during interpersonal interaction for balance support.

Besides that finding answers to this objective is essentially important with regard to prospective applications in the field of assistive robotic solutions for balance rehabilitation.

Hence, another aim of this work is to set the prerequisite for an engineering adaptation of fundamentals of interpersonal coordination for light tactile balance support.

In the first part of the dissertation, the author presents a recapitulation of the state of the practices in interpersonal interaction, postural control and the provision of haptic support for balance control.

The second part introduces the theoretical background, namely an ecological perspective on the perception of social affordances in clinical settings. It presents the method of light interpersonal touch as a potential therapeutic tool for balance rehabilitation.

The third part describes the studies on light haptic support for balance control, that were performed for this work. In order to examine changes in postural stability during the provision of haptic support with various sensory feedback availability, different variables based on the COP velocity were collected. Significant conclusions include measures of the postural stability of the contact receiving person, strength and temporal interpersonal coordination.

The first study investigated the outcome of visual and haptic sensory information on interpersonal balance coordination in a joint action scenario which we called maximum forward reaching. The aim was to identify the spontaneous interpersonal coordination for balance support and to adjust the leader-follower relationship by setting up an irregular dependent relationship. It detected that temporal movement coordination depends on the existence of an external object target and the visuotactile interpersonal context. Without the presence of an external object target the strength of the interpersonal coordination was highest.

The second study examined the dynamic interpersonal coordination during exercises for balance rehabilitation between a clinician and elderly subjects with balance insecurities. It examined the effects of exercise difficulty and the support mode (active facing to / passive facing away) on the interpersonal coordination of both partners. In addition, forces between the two were measured in order to find out how much force a physical therapist (PT) actually applies when stabilizing a subject. It observed interpersonal coordination to be strongest when support was provided passively. However, the provison of active support produced greater sway reduction than the passive one.

The third study was mainly executed based on the interdisciplinary project „Robotic light touch support during locomotion in balance impaired individuals“ (ROLITOS) within the 9th call of the TUM International Graduate School for Science and Engineering. The project aims to combine the expertise of human movement scientists and engineers with a focus in robotics from the Technical University of Munich.

The engineering aim resides in the translation of the principles of human-to-human interpersonal coordination for light tactile balance support into a robotic solution. This dissertation includes an outlook on the results of this interdisciplinary work. In this study the author of this dissertation and colleagues asked the question of how simple the control mode of a robot during human-robot interaction for balance support can be to still evoke a response in a human participant. It showed that robotic haptic support was effective in influencing the control of body balance of the participant. Similar effects on reducing body sway of robotic touch and human interpersonal touch were found.

Study findings were successful in improving the understanding of light haptic support for balance support, hence achieving the objectives of this dissertation.

Finally, a comprehensive discussion and the perspectives towards the use of light interpersonal touch as a manual handling tool for balance rehabilitation are presented in the last part of this dissertation.

2 General introduction

The control of body balance during the execution of various every day activities, such as walking, reaching, or running, relies on successful sensory integration. The visual and vestibular channel gives helpful input. Also proprioception helps to maintain control of body balance by giving the encephalon input regrading the location of the segments to support it to make suitable movement corrections to keep control of body balance and avoid falling. Our eyes work for the visual anchor which gives input about the orientation of a human referring to the surrounding as well as close objects that might worsen postural control. More valuable information about for example the position of the head related to the body is added by the vestibular system. After the integration of sensory information necessary movement adaptations to maintain control of balance can follow. Hence, integrating sensory information enables the encephalon to produce adaptive mechanisms to achieve successful modification of posture (Peterka 2002).

However, with increasing age the performance of sensory systems seems to decrease (Kerber, Ishiyama et al. 2006). Abnormalties and reduction in functioning (Sullivan, Rose et al. 2009) or lower limb muscle weakness (Aniansson, Hedberg et al. 1986) can be mentioned to demonstrate such a reduction in the performance of the sensory systems. A greater risk of falling and a poor control of body balance can be the result of these declines. Moreover, people who had a fall tend to develop a fear of falling. They often end up in hospital stays or long term care facilities which makes them inactive members in the community. That is why evidence-based fall prevention in clinical settings is essential to decrease this severe public health problem. In order to advance evidence-based fall prevention the understanding of how to improve interpersonal caregiver-patient coordination and postural control is much-needed. A broadly accepted approach to improve postural control is the provision of haptic support (Jeka and Lackner 1994).

Two types of haptic support can be considered. The first one is the provision of stationary or moving object support (Fung and Perez 2011) and the second one is interpersonal support to improve balance control (Johannsen, Wing et al. 2012). The latter type will be especially interesting for the current work which uses interpersonal haptic support to try to improve control of body balance.

However, the first type mentioned is the more prominent way of using haptic information. Few studies have investigated the second type, namely interpersonal haptic support for balance control (Johannsen, Guzman-Garcia et al. 2009). Especially light interpersonal contact support is of interest for this work since it is assumed to be an interpersonal haptic form of communication between caregiver and patient.

According to the core assumption that light IPT facilitates patient's postural stability, this dissertation is devoted to the study of a haptic cue provided in a light touch fashion during interpersonal coordination for balance control.

In addition, the threatening shortage in clinical staff can cause lacks in patient supervision, safety and support. Light interpersonal touch features an interesting strategy which reduces stress on the therapist when supporting control of body balance and concurrently it providing balance support, while at the same time it promotes the practice of subjects' postural control during standing (Johannsen, McKenzie et al. 2014).

The study of human-to-human interpersonal balance support strategies can also serve as groundwork for future automated haptic assistive devices which could have a large input in the future of fall prevention.

Beyond those firstly presented scientific theoretical considerations, the current work was highly energized by personal interest.

Firstly, former working life in the clinical setting with stroke patients showed that some of the patients recovered very poorly which forced them to become inactive members in society. This fact motivated the author to contribute to balance rehabilitation.

Secondly, day to day life situations seem to already demonstrate that light haptic cues are being used for balance stabilization. When walking down the street one can see cane users actually using their support tool periodically to stabilize control of body balance by making contact with the ground level. When entering a dark room humans tend to lightly touch the wall in order to get some orientation and find the light switch. In clinical settings a light touch from the therapist can help to lead the patient in the desired direction.

Hence, these everyday life observations are consistent with the literature, which has demonstrated that light haptic support is able to stabilize human posture. Moreover, it seems haptic cues can cause potential positive interpersonal psychosocial effects. Touch brings emotional support when a patient is distressed e.g. before surgical operations and creates sympathy and emotional well-being.

Building on the described knowledge from previous studies, the purpose of this work was twofold. It consists of three specific study aims which refer to the problem statement of this dissertation which is stated on the homepage of the chair of movement sciences of the departement of sports and health sciences of the TUM:

"In clinical settings caregivers provide manual support to patients with impaired control of body balance. Thus interpersonal haptic support provides an ecologically valid and effective strategy for controlling a patient's fall risk. ***However, from a therapeutic point of view restricting a patient's movement degree of freedom by grasping his or her body to support the weight is inadequate for the purpose of practicing own control of body balance. "***

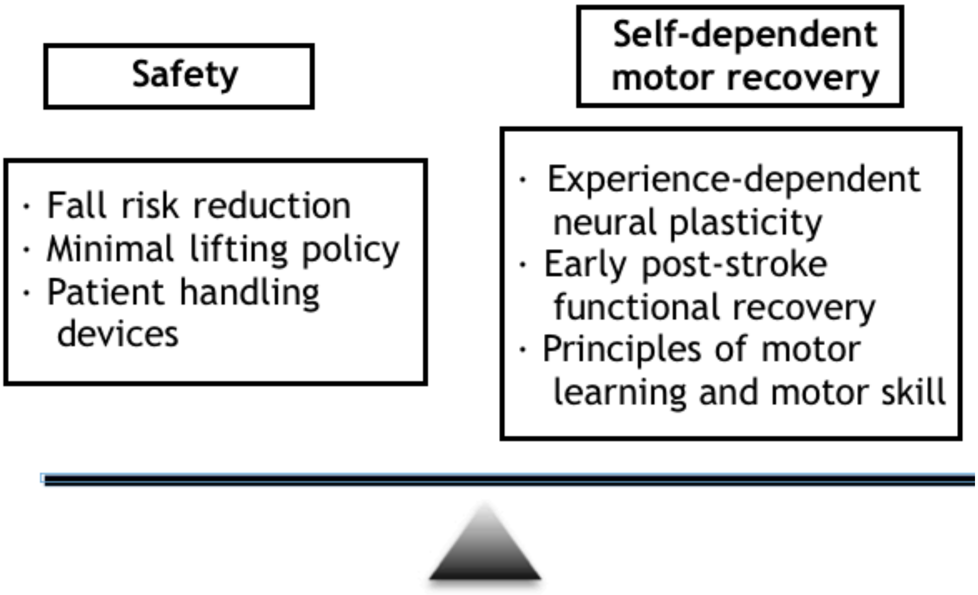


Figure 1: Trade-off between health and safety and atient motor recovery.

A more promising strategy from the author’s point of view and also stated on the homepage of the chair of movement sciences at TUM would be “balance support provided in a ‘light touch’ fashion.“ The trade- off between health and safety and motor recovery, might be found in the light touch provision which is supposed to be an adequate method which meets both requirements; safety provision and allowance of self- dependent motor recovery (see figure 1).

This work aspires as staed on www.bewegungswissenschaft.sg.tum.de/forschung/publikationen/ to “improve the understanding of interpersonal dynamics of light touch in general (study aim I)“ and in a next step to improve the understanding of “caregiver- patient interaction during light interpersonal haptic support in particular (study aim II).“ The third objective is to investigate the translation from “human-to-human interpersonal coordination for light haptic balance support into a robotic solution (study aim III).“ This third aim was investigated in a joint study with colleagues from the field of dynamic human-robot interaction.

The first part of this dissertation reviews preliminary work on the study of interpersonal coordination, postural control and light haptic balance support.

3 General principles of interpersonal coordination

This work will begin with an overview about the general principles of interpersonal coordination. In the first section, the reader is provided with relevant information in order to better understand interpersonal coordination and coordination processes.

3.1 Interpersonal coordination and coordination processes

Humans have an impressive talent to harmonize performance with a partner to reach a common goal. In her paper: *The role of shared visual information for joint action coordination* Cordula Vesper refers to (Wolpert, Doya et al. 2003, Pesquita, Whitwell et al. 2017) and notes that, "in order to perform joint actions such as walking hand in hand or moving a table together, at least two individuals should harmonize their performance while coincidentally dealing with the challenges which occur from not having direct access to each other's sensorimotor processes (Vesper, Schmitz et al. 2016)."

Certain mechanisms which are involved during interpersonal coordination in a joint action can be defined (Sebanz, Bekkering et al. 2006). That is to say, that joint attention offers a method for dividing common intuitive incoming information and navigating thoughts to the equivalent situation. The interplay between perception and action enables people to create representations of the target of a partner and to anticipate the result of the reaction. Through creating joint action representations we permit the prediction of behavior built on specific situations which happen in our sorrounding, irrespective of monitoring the situation. Action coordination can be realized by being able to incorporate the time and space of actions of a partner in the performance of oneself (Sebanz and Knoblich 2009). Cooperation, collaboration and competition have been classified as interpersonal sensorimotor interactions (Jarrassé N. 2012). While roles are assigned a priori in cooperative actions that is not the case in collaborative interactions, which do not organize a priori role tasks. Presumably all along interpersonal coordination between caregiver and patient such action coordination occurs.

This coordination can be seen as a cooperation in a joint task between two individuals, since the roles are assigned a priori in clinical settings. As such we can reasonably conclude that caregiver and patient should find a way to cooperate in order to achieve successful interpersonal balance rehabilitation.

3.2 Interpersonal sensory information and communication

Communication happens via social cues. Visual as well as postural cues are being used in day to day life situations but also gestures and haptic cues. With the multiplicity of communication cues the question arises what dictates which cues and coordination forms the use by the interactionists during the execution of a goal oriented task with a partner.

In order to tackle this question the first study of this dissertation was dedicated to study interpersonal communication tools, such as sensory information during a goal oriented joint task in order to enlarge the level of knowledge on which cues the interactionists rely on during interpersonal coordination (see chapter 9).

It should be stated that authors can set different focus on sensory information and communication in their studies, thus a concrete boundary between sensory information and sensory communication is difficult to determine.

3.2 Interpersonal coupling

Interpersonal coordination often occurs during joint action. In such actions various people synchronize their movements to be able to reach a common goal by executing a task together. Specific temporal and spatial adjustments need to be made in order to achieve a well performin interpersonal coupling. As across team members when playing basketball or between piano players during a piano duet. The question which arises is: How do individuals synchronize their performances toward a common action goal?

Although tasks can be performed by one individual only, such as singing a song or moving once feet to music, the performance can become more skillful and quick when executed as a group (Issartel, Gueugnon et al. 2017, Bishop and Goebl 2018). Sometimes motor tasks require interpersonal coordination in order to be favorable executed. Individuals interact interdependently during the lifting of a box or when they talk to each other, they perform motor synchrony (Bosga and Meulenbroek 2007 (Bosga, Meulenbroek, & Cuijpers, 2010).
They mirror the spatiotemporal models of their partner deliberately or involuntarily. (Lakin and Chartrand 2003, Shockley, Santana et al. 2003). However, during some activities interpersonal coordination happens rather randomly, such as during a conversation. In the paper *Visual influences on postural and manual interpersonal coordination during a joint precisison task,* Athreya and colleagues use the words from Marsh and Richardson (Marsh, Richardson et al. 2009, Shockley, Richardson et al. 2009) saying that motor coordination embodies the social, cognitive and linguistic coordination necessary for effective communication (Athreya, Riley et al. 2014).
The understanding of the general mechanisms and processes which facilitate interpersonal coordination is of importance to improve motor coordination and also in order to promote social and cognitive interpersonal coordination.

Coupled systems can demonstrate complex behaviors that will not emerge from a single, simpler component system (Sebanz and Knoblich 2009). This is an important issue regards the means by which two actors' movements become coupled. So to speak, how two people become reciprocally linked or connected by a medium that permits their movements to influence and constrain one another (social coupling). The nature of the coupling can influence the nature, strength, and stability of interpersonal coordination (Athreya, Riley et al. 2014). One way to link two individuals is via mechanically coupling. When two individuals transport a table together, each individual's lifting forces have an effect on the partner's performance (Bosga and Meulenbroek 2007).

Another way of coupling is informational or perceptual coupling which can occur via different perceptual modalities, such as vision or touch. Athreya and colleagues set up a joint action precision pointing paradigm where participants were asked to harmonize their finger movements when they could see the others' whole body movements or only see the outcome of the others' performance (Athreya, Riley et al. 2014). They conclude that interpersonal postural coordination appeared to emerge sponta- neously as a result of visual entrainment.

In general, when perfoming tasks together, people become unknowingly coupled at several levels (motor, perceptual and cognitive) as suggested by Knoblich and colleagues (Knoblich 2011). An example for a motor level coupling has been demonstrated by Richardson and colleagues. Humans on rocking chairs coordinate their performance just like they were mechanically connected (Richardson, Marsh et al. 2007). Hasson and colleagues show perceptual coupling in their study demonstrating that when individuals look at a target from from contrasting views, they take up the viewpoint of the other person (Hasson, Ghazanfar et al. 2012). Overall, previous research on perceptual coupling by Gagnon and colleagues (Gagnon 2015) has demonstrated that humans are able to estimate multiple actions, such as another person's reach (Rochat 1995), sitting (Stoffregen, Gorday et al. 1999), and reach by bouncing (Ramenzoni, Riley et al. 2008, Ramenzoni, Davis et al. 2011).

3.3 Dynamics of interpersonal coordination

Studies on a interpersonal coordination were already performed around 1960. It started with the recording of videos for research on communication (Cornejo, Cuadros et al. 2017).

A study by Schmidt and colleagues demonstrated that the motoric performance of humans is likely to be coordinated (Schmidt 2008). When having the task to smoothly coordinate body parts such as legs, people demonstrated a performance development alike to bimanual movement coordination across limbs. The latter was detected to be a dynamic process by mathematical calculations. The infrequent stategy of the interactionists can be influenced by the perceptive as well as by the dynamic conditions.

Studies on social identity characteristics which observed for example two people regarding factors such as compatibility, empathy or togetherness present influential attributes of interpersonal movement strategies. The strength of complementary actions reflects the strength in subjective connectivity learnt in daily life communication (Zhao, Salesse et al. 2017). Tested has also been the consequence of sympathy on interpersonal motor coordination (IMC). In a study in which two individuals were asked to touch the finger of the partner the researchers analyzed the fixation tendencies. Moreover the sympathy factor of the partner was grouped into three categories. Base, sympathy and no feeling for sympathy. Their results demonstrated a relationship amongst the interpersonal motor coordination and the fixation behavior just for the symphathy category (Zhao, Salesse et al. 2017).

Hence, the psychological and social characteristics of the individuals during interpersonal coordination do play a role and are being recommended to be inspected for the interpretetation of individual motor coordination.

With respect to the study of interpersonal coordination in clinical settings, psychosocial factors are of importance since patients are a part of a vulnerable population and especially mental health plays an especially large role in addition to the physical component in rehabilitation.

Interstingly the attractivness of a partner can influence the interpersonal synchronization between individuals. Physical more attractive avatars improved the motoric performance of the partner as demonstarted by Zhao and colleagues in a study on interpersonal performance with multiple avatars (Zhao, Salesse et al. 2015). Therefore, the physical look of a person certainly influences the interaction between individual.

When two humans perform a task together both most likely synchronize with eaxhc other somehow from a movement perspective (Varlet, Stoffregen et al. 2014). Interestingly postural control can not only be affected by mechanical perturbations but is also responsive to social factors. When simulating an ocean voyage through perturbations researchers had participants standing facing to each other and away from each other. Facing to each other improved the strength in synchronization of postural control between the participants more than facing away from each other (Varlet, Stoffregen et al. 2014). The authors concluded that being able to see the partner increased the competence to counterbalance for movement of a boat. So to speak a rather “soft“ competence such as being able to make eye contact to a partner is able to affect the balance synchronization when humans concurrently adapt postural control of body balance in answer to “hard“ machine driven requirements.

The second study of this dissertation (see chapter 10) will refer to this “hard“ and “soft“constraints. The findings will be discussed in more detail in the general discussion part (see chapter 12).

To conclude this chapter on general principles of dynamic interpersonal coordination it is worth emphazising that when joint action partners coordinate their movements they may share information but at the same time face differences in task-relevant knowledge and roles. To give an example, a blind person can receive tactile visual or verbal cues from a guiding partner. Diverse joint tasks demonstrated spontaneous interpersonal coordination (Varlet, Marin et al. 2011).

Implicit observation of a partner in a joint precision task improved manual performance as well as interpersonal coordination (Athreya, Riley et al. 2014).

Moreover, verbal communication during a joint problem solving task is able to influence interpersonal coordination regardless of whether visual feedback about the partner was available (Shockley, Santana et al. 2003).

A possible explanation therefore might lie in shared speaking patterns which mediated the interaction (Shockley, Baker et al. 2007).

Lastly, haptic interactions provide powerful sensory information for interpersonal coordination (Johannsen, Wing et al. 2012). The primary focus of this dissertation lies in the haptic support for control of body balance and will be circumstantially discussed in chapter 8.

4 Principles of postural control

After the overview on general principles of interpersonal coordination a summary on the principles of postural control will follow in the next section.

4.1 Biomechanical and sensorimotor elements of postural control

The interplay of many factors regarding body kinematics is needed to achieve successful postural coordination and postural stability. Active and passive torque mechanisms are being used to allow quiet standing. Acccording to Vette and colleagues stiffness and damping are factors which the passive torque depends on while the CNS controls the active torque with the help of body movement such as e.g. muscle contraction (Vette, Masani et al. 2010).

The COM of the body lies further forward than the ankles (Johannsen 2017); consequently, even in quiet stance position on a firm surface the muscles must exert a torque in the ankle to stop the body overbalancing forwards (Wing, Johannsen et al. 2011). Assumingly as stated by Johannsen and colleagues: " this torque may need to be significantly increased when balance is disturbed (Johannsen, Coward et al. 2017)."

In this dissertation the performance of the postural control system is mainly presented in COP velocity. According to Masani and colleagues knowledge on sway velocity is of enormous importance for control of body balance (Masani, Popovic et al. 2003).

The control of body balance requires a dynamic interplay of sensory information, thus is considered to be a complicated expertise (Horak 2006). According to Horak and colleagues somatosensory, vestibular and visual systems provide sensory information (Horak 2006). The combination of those three factors depends on the aspired output of the task as well as on the environment (see figure 2).

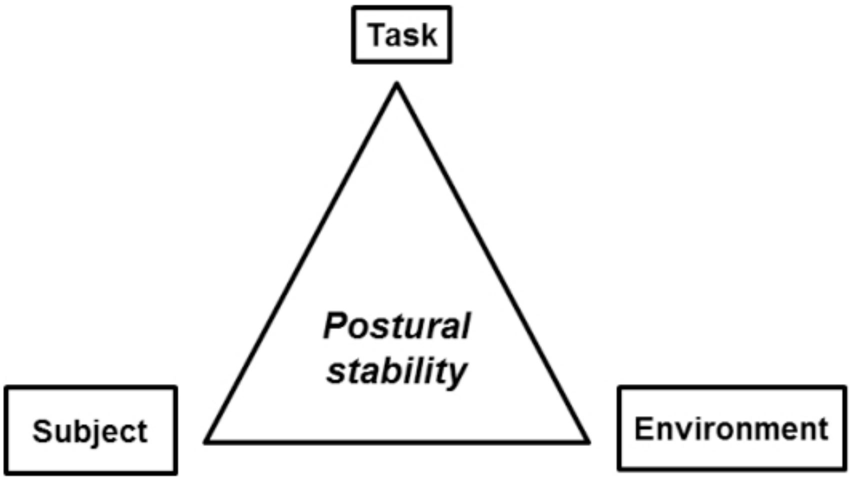


Figure 2: Factors of postural stability. Analogue to (Albertsen 2012).

Movement response strategies depend on the aspired outcome the subject has as well as on the practical knowledge the subject already made (Horak 2006).

The complexity which the balance exercise requires as well as the subject's potential to perform the control body balance define the necessary cognitive processing input which is required to maintain postural control. However aging and diseases can affect the subject's health thus the performance of the postural control system.

Multiple mechanisms underlie postural control and need to be taken into consideration when studying interpersonal coordination for balance control.

The methods which have been used in this work in order to determine control of body balance will be introduced in chapter 8.

4.2 Upright balance

How do humans actually maintain upright balance in standing? Although this process seems easy for most individuals upright standing is a complicated skill based on the successful interaction of various factors.

A well-accepted reference model which inspired most postural control study is analogy between a standing person and an inverted penduluum (see figure 3) (Peterka 2002, Blumle, Maurer et al. 2006).

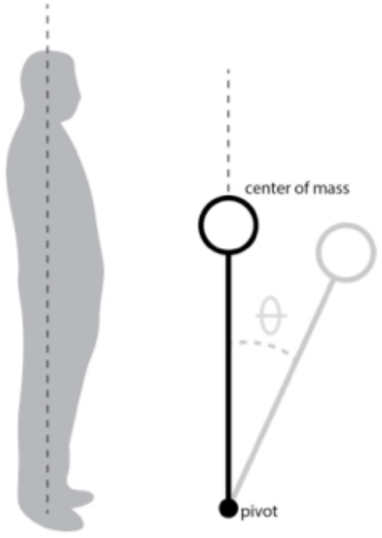


Figure 3: The analogy between a standing patient and an inverted pendulum. Adapted from (Winter 1995).

Nonetheless successful postural stability requires coordinated control of various body components (Ting 2007). Different kinds of balance strategies can be used to achieve postural stability (see figure 4). Via rotation around the ankle (Mauerer and Peterka 2005) as well as around the hip (Reeves, Narendra et al. 2007) postural control can be maintained when thinking of the inverted pendelum approach.

Balance in general and balance control in specific can be seen as two different aspects. When thinking about balance we usually expect minimum postural sway up to no sway at all. Whereas when talking about balance control we need to think about what needs to be optimized in order to achieve more balance stability. Thus, less sway is not necessarily an indicator for well functioning balance control. In order to be able to make a statement on balance control it is of importance to see the balance performance with respective to the balance baseline of an individual.

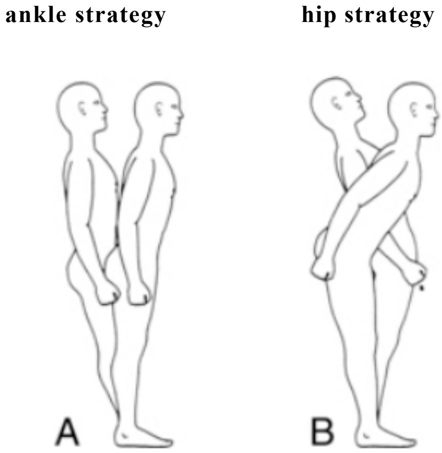


Figure 4: Examples for balance strategies.

Adapted from (Kisner 2012).

4.3 The control of balance via signal transmission

The combination of sensory information based on various origings is essential to achieve successful postural control. A well-functioning combination of information leads to an efficient postural control which depends on different peripheral systems and the central processing by the CNS (Albertsen 2012).

Sensory feedback is of high importance, however time delays due to the signal transmission and processing can affect the feedback loop. Corrective motor commands and the corrective torque can support balance control but with a time delay (Peterka 2002, Maurer and Peterka 2005).

Different signals such as e.g. the orientation of a target in the surrounding, head position, information on tendons and fibres are the basis for sensory information (Albertsen 2012). Due to the execution of motor commands such as muscle contraction as well as signal communication and transformation time delays occur (Peterka 2002, Maurer and Peterka 2005).

Sufficient sensory integration needs the intactness of the different peripheral sensory systems and the central processing by the CNS (see figure 5), both of them are negatively impacted during aging and can be affected by pathological problems which can cause balance impairments. Those different sensory systems provide the CNS with incoming proprioceptive inputs, visual cues or vestibular information.

The participation of each of these modalities for postural control in upright stance is elevated in the sensory organization test (Horak 1987). Proprioceptive information provides information about the structure of the surface by giving input on e.g. the length of the muscle (Albertsen 2012). The tactile receptors in the feet could also provide information, in addition to the orientation from mechanoreceptors in joints and muscles (Maurer, Mergner et al. 2006). Another orientation cue comes from the visual system which produces insights about vertical awareness. Lastly, Shumway-Cook and colleagues believe that the CNS receives vestibular information with a gravito inertial reference respective to angular acceleration and linear acceleration (semi-circular canals) and head tilt relative to gravity (otolithic system) (Shumway-Cook and Horak 1986).

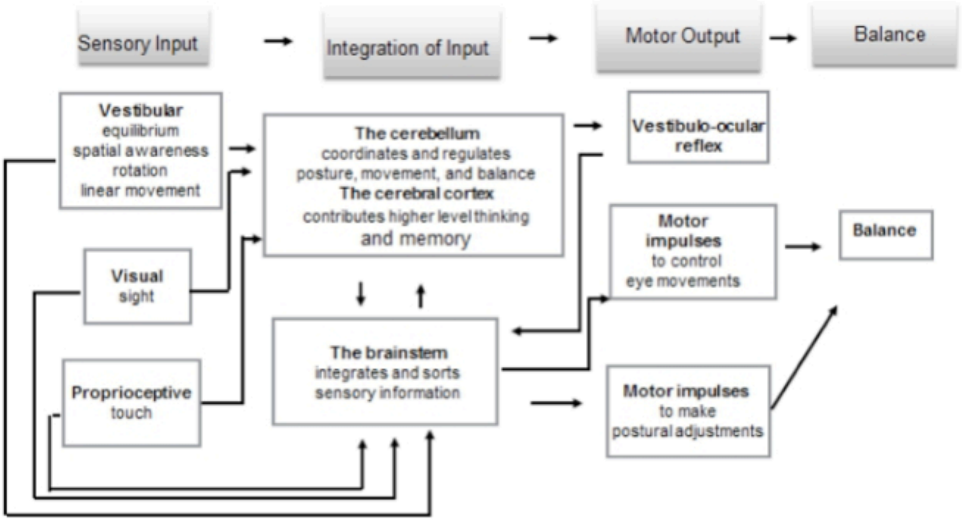


Figure 5: The Human Balance System. Adapted from Vestibular Disorder Association (Association 2018).

4.4 Combination of different sensory information

Multisensory integration by combining different sensory inputs and thus creating a mutual reference frame is already discussed in research on postural control (Jeka, Oie et al. 2000).

The effect of haptic information and its interplay with the other aforementioned sensorimotor inputs for balance rehabilitation is of particular significant interest. The understanding of how the CNS combines orientation cues for control of body balance challenges researchers. On these grounds this current work aims to improve the understanding of such a combination of different sensory information during interpersonal coordination for balance control.

Regarding the mechanisms of multisensory integration, current literature provides various explanations. While some argue for a linear process such as constant sensory weighting (Fitzpatrick, Burke et al. 1996) others highlight the aspect of nonlinearities such as different weighting attribution to sensory inputs in multisensory integration activity (Jeka, Oie et al. 2000, Peterka 2002).

Lina Ting even argues that the summation of various sensory channels might be insufficient for control of body balance (Ting 2007). She proposes an internal model to capture the multisensory integration.

Internal conclusions can be the result of the act of restoring of provocations from the outside and might be more easy managed for the preparation of movement execution (Maurer, Mergner et al. 2006). Dynamic stimulus dependent adjustements appear when sensory information is being added to control body balance (reweighting) under various conditions of the surrounding (Peterka 2002).

Jeka and colleagues used a moving room paradigm in which they manipulated visual and haptic cues (Jeka, Oie et al. 2000, Oie, Kiemel et al. 2001). Young participants applied intrasensory as well as intersensory reweighting to maintain postural control (Oie, Kiemel et al. 2001). Intrasensory reweighting causes a fall off of gain of a perturbed improper modality and intersensory reweighting represents a change away from imprecise cues towards more precise sensory modalities.

Study results about haptic light touch provision causing an instantaneous stabilizing effect, are being supported by studies on galvanic vibration (Peterka 2012) and electro tactile feedback (Kaczmarek, Webster et al. 1991).

With respect to the effect of haptic light touch for balance control in interpersonal interactions for balance control in the current work, the aforementioned background regarding multisensory integration and reweighting plays a crucial role. This background also impacts the question concerning restoration and compensation in rehabilitation which will be a part of the overall discussion (see chapter 12).

4.5 Motor skill acquisition

With respect to balance rehabilitation it is necessary to introduce motor skill acquisition. The author claims that balance support in a light touch fashion has advantages for rehabilitation which the limitationing of a patient by grasping the body to stabilize the patient might not have, this statement needs justification. Motor skill acquisition theory should help to justify this statement.

Commonly a contact provider such as a therapist provides passive manual support to a contact receiver such as a patient in order to improve control of body balance. in an effort to provide more appropriate proprioceptive feedback. However, it should be questioned if this is the optimal technique to show a contact receiver what he or she should be able to do on his or her own (Muratori, Lamberg et al. 2013).

Without a doubt, safety is of high importance in clinical settings. Thus the therapist should be standing close to the patient. However when viewing the patient as a learner haptic support can be seen as a simultaneous response. As a result, this support turns partially into a controlling criterion of the interaction. The contact receiver could get dependent on that response. Although performance may improve, the patient may be delayed in learning the task as the patient was not in the need of dealing with the movement challenge repeatedly during practice.

In the case manual guidance is needed in order to guarantee safety which is of the utmost of importance, a light touch might be the more promising strategy for balance rehabilitation. Finding the trade-off between safety and motor recovery is one of the keys for successful balance rehabilitation**.** The experience dependent neuroplasticity of a patient and motor learning principles are supposed to be especially essential to achieve long lasting self-dependent improvements in the postural system. The practice of a patient’s own control of body balance is, from a therapeutic point of view, very important. According to Newell and Bernstein (The Coordination and Regulation of Movements, Pergamon, London, 1967) the understanding of coordination greatly affected the growth of the ecological approach to action (Bernstein 1967) (see chapter 7).

According to Spray and Newell 1986 „motor skill acquisition is achieved by the interplay of subject related (biomechanical, musculoskeletal, sensory, cognitive), environmental and task inherent factors (Spray 1986)."

Impaired control of body balance is often caused by shifts in those factors because they can lead to decreased control of body balance (Horak 1996).

The mentioned factors which are responsible for motor skill acquisition were manipulated in the experiments of this work in order to improve the understanding of interpersonal haptic coordination for balance control:

- The availability of sensory information (environmental factor) was manipulated (see study I, II, III).
- Healthy young individuals (see study I) and elderly individuals with balance insecurities (see study II) (subject related constraints) were tested.
- An increasing difficulty level of balance exercises (inherent task factor) was used in order to challenge the control of body balance and detect its influence on IPC (see study II).

The CNS must continuously manage the interaction between the constraints and all changes within one of the different constraints. In conclusion, the CNS perceives self-motion and external motion from the environment and simultaneously via sensory cues from vision, proprioception in the leg muscles, the vestibular system and finally tactile feedback from the soles of the feet (Diener and Dichgans 1988, Horak 1996).

With respect to this current work, haptic light touch cues for balance support are in the focus of our interest. As already mentioned, from a therapeutic point of view restricting a patient‘s movement degree of freedom by grasping his or her body to support the weight is inadequate for the purpose of practicing own control of body balance. The justification for describing this technique as inadequate lies in the assumption that a trade-off between a patient’s health and safety on the one hand and his or her motor recovery on the other hand should be guaranteed.

Specifically a reasonable fall risk reduction and the experience dependent neuroplasticity of a patient need to be meaningfully counterbalanced.

Without a doubt, minimal lifting policies, patient handling devices and physical support strategies are necessary in order to reduce fall risks, but allowing optimal independent patient motor recovery should also be incorporated in balance rehabilitation. Therefore, allowing the patient to use the experience dependent neuroplasticity, motor learning as well as skill acquisition principles is essential for independent long lasting rehabilitation. Practicing one's own control of body balance is indispensable in order to improve motor skills through practice. The input of additional sensory cues, such as light touch in training situations for balance rehabilitation, is assumed to be a valuable and promising strategy. Particularly, the practice of one's own control of body balance for independent rehabilitation could be transacted in a light haptic support interaction with a therapist.

5 Augmenting body balance with light touch

In the following section, a review of preliminary work on light touch for control of body balance will be presented. A summary of the psychosocial effects of interpersonal human-to-human light touch will conclude this chapter.

The additional sensory cue which is being used in this work is called light interpersonal touch. The term light touch incorporates cutaneous and proprioceptive cues enclosed in skin, muscles and joints of the arm and, especially for this dissertation, of the finger when providing light touch to a partner.

In the following section, this work presents a review of preliminary work that has been performed to test the effect of haptic support for balance control. Two methods of providing haptic support are presented.

Practically speaking, one method is passive haptic support. This means that the tactile reference (object or human contact) is provided to the contact receiver who is less involved in the touch exchange.

The second method is called active haptic support. In this method the contact receiver is more involved in the provision of haptic support. Further explanations on active and passive interpersonal touch will be addressed in study II (see chapter 10).

5.1 „Active“ light touch for balance support

Studies on augmenting body balance are usually largely inspired by the work of of Jeka and Lackner. Their studies explained how the input of light touch of the finger on an external reference point influenced control of body balance (Jeka and Lackner 1994, Jeka 1997).

Lackner and colleagues had subjects stand in tandem romberg stance (heel to toe) while touching a force transducer using light touch only. In case the executed force by the subject passed over 1 N a cautionary sound popped up. The availability of vision was also manipulated. In one condition the participant had full vision while in the other conditions there was no access to vision.

Light touch decreased mediolateral sway to the same level regardless as to if vision was available or not. In a force condition that allowed participants to apply the force they wanted, subjects used 3 to 4 times extra force as was consistent in the light touch condition. However, the force condition induced similar low levels of sway similar to the situation with light touch. A larger correlation and a smaller lag were found in the force touch condition. Lackner and colleagues interpreted these results and proposed that the shear force at the finger produced postural adjustments to keep the provision of light touch with low regular force. The effectiveness of such a haptic input route, in comparison to regular proprioceptive and tactile ressources standing by when no vision is available ended up in sway reduction. Contrarily the force touch condition could have led to a reduction in sway by physically stabilizing control of body balance.

However, Johannsen and colleagues proposed a different interpretation. More heavy touch provision could have led to a more precises sensory input on sway. That could have caused quicker and more specific substitutional postural control regulations (Wing, Johannsen et al. 2011).

In summary, the benefits which were achieved by the studies by Lackner and Jeka were that touch input provided by the fingertip assisits to create a precise picture of the body position due to the fixed reference point provided in the environment, improving control of body balance (see figure 6) (Albertsen 2012).

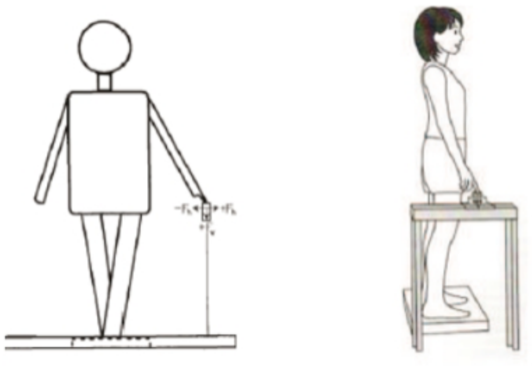


Figure 6: Typical light touch with fixed support. Modified by Albertsen 2012: (Jeka and Lackner, 1994) (on the left) and (Kouzaki and Masani 2008).

5.2 Passive light touch for balance support

The decline of sway appears in a ‘passive’ light touch fashion e.g. when a human who takes part in the interaction with another human touches the skin of the contact receiver (Wing, Johannsen et al. 2011).

In terms of an interpersonal coordination between two individuals, passive support in this dissertation is defined in the way that the support is provided from the contact provider to the contact receiver who is less involved in the interpersonal haptic exchange (see study I).

An example for a passive haptic support study is an experiment by Rogers and colleagues (Rogers, Wardman et al. 2001). Participants stood with flexible light contact at the leg or the shoulder. In both cases the moving back and forth was decreased, although the passive support was of highest benefit for control of body balance the higher the touch was being performed to the body. Reasonably a certain degree of sway ends up in greater variation in force, or exertion of the contact provider, at the higher segment of the body (Wing, Johannsen et al. 2011).

A colleaction of inputs from those origins, meaning when the origins were applied together, led to even greater sway reduction (Rogers, Wardman et al. 2001). This finding was verified by Dickstein and colleagues when using active light touch, by using two index fingers to provide the touch rather than using one index finger (Dickstein 2005).

5.3 Interpersonal light touch

After having presented the classical active and passive light touch paradigm, this next chapter introduces the general principles of interpersonal light touch.

Starting with an overview of the effects of interpersonal light tactile sensations on control of body balance, followed by its overall influence on emotional well-being.

5.3.1 The effects of interpersonal light tactile sensations on control of body balance

Balance control necessitates as also stated by Steinl et al. 2017 in study II *Interpersonal interactions for haptic guidance during balance exercises* “the integration of self-motion information from multiple sensory modalities (Blumle, Maurer et al. 2006). The postural control system is able to convey self-motion from primary motion detectors and also from actively earned or passively received light contact with the environment (Rogers, Wardman et al. 2001). Human touch, a non-weight bearing contact which possesses motion dynamics of its own, can also provide light haptic information to stabilize another human during quiet stance (Johannsen, Wing et al. 2012).“

Building on this knowledge, light interpersonal touch could be a promising strategy and therapeutic tool to provide balance support for patients with impaired control of body balance. Human interpersonal light touch is thought to combine the effects of psychosocial factors and guidance of postural control, such as in clinical settings during the interaction between caregivers and patients. Hence, it might be able to cover the requirement of the New Zealand patient handling guidelines which demand the caregiver to reassure and guide the patient (ACC 2012).

Several of the studies by Johannsen and colleagues greatly inspired this work. They demonstrated the effects of interpersonal light touch on balance in healthy individuals (Johannsen, Wing et al. 2012), the elderly (Johannsen, Guzman-Garcia et al. 2009) but also in individuals with balance disorders, such as children and adolescents with cerebral palsy (Schulleri, Burfeind et al. 2017).

In one study they asked pairs of healthy individuals to either stand in bipedal stance or tandem romberg stance with eyes closed. They used threee ways to provide light touch: finger to finger contact, finger to shoulder contact or no contact (see figure 7). Sway decreased significantly in the interpersonal light touch when comparing it to the condition without touch involvement. Sway was reliably less with interpersonal light touch compared with no contact in general (Johannsen, Wing et al. 2012).

Greater sway reduction had been demonstrated when the touch was applied to the upper body part (shoulder) than when being applied to the lower part (finger).

This is analog to the finding of Rogers and colleagues who also found the light touch provision at shoulder level to be most effective (Rogers, Wardman et al. 2001).

Figure 7: Interpersonal light touch for balance support.

Adapted from (Johannsen, Wing et al. 2012).

5.3.2 Inducing emotional well-being through interpersonal touch (IPT)

Touch is of importance in everyday social interactions beginning at birth and continuing for one's entire life. Still, there is a lack of scientific research on the matter of interpersonal touch (Gallace and Spence 2010). The disciplines which do report results on the study of interpersonal touch are psychology, neuroscience and anthropology.

A significant important factor which inspired this work's focus on haptic interaction, is the idea that the emotional well-being of a patient plays a noteworthy part in the balance rehabilitation and learning context of a patient. As human touch induces emotional well-being, interpersonal light touch support for balance rehabilitation might be even able to provide psychosocial benefits for the patient in addition to the effects on postural control.

6 Humans with impaired control of body balance

Since interpersonal light touch is supposed to support balance impaired humans, the next chapter will provide more insight into the topic of balance impairments in humans and the consequences of that lack in control of body balance.

6.1 Risk factors leading to falls

With increasing age humans show lessening in sensory systems (Kerber, Ishiyama et al. 2006, Serrador, Lipsitz et al. 2009). This leads to a higher risk of falling and poor postural control.

A major problem which explains serious injuries or death amongst the elderly is falling (Tinetti, Doucette et al. 1995). People who have fallen are also likely to develop a fear of falling. Often, they end up in hospital stays or long term care facilities which makes them inactive members in the community. Several risk factors of falling have been reported and are usually split into intrinsic and extrinsic risk factors. While poor vision or unstable walking surface are examples for extrinsic factors, intrinsic factors could be a result of psychological changes associated with aging (Lajoie and Gallagher 2004).

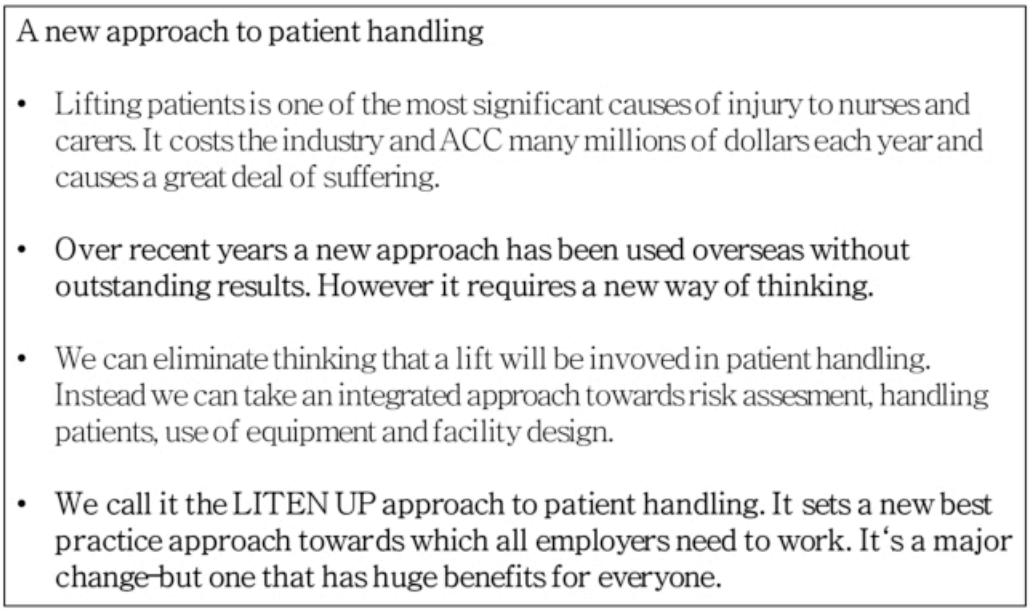
Four major categories were established to summarize factors leading to falls and fall-related injuries. Biological risk factors, Socioeconomic risk factors, Environmental risk factors and Behavioral risk factors. All four categories mutually depend on each other and should not be viewed as stand alone categories (WHO 2007).

6.2 Manual handling guidelines

One risk factor that catches the attention of the author of this work, is the lack of exercise which is listed as a risk factor in the behavioral risk factor category. Efficient prevention programs for fall risk used multifactorial approaches since fall prevention is challenging (Tinetti, Mendes de Leon et al. 1994). Falls in older adults are associated with functional decline and fragility. An increased annual fall incidence rate and increased prevalence of reported falls in older adults' demands more fall prevention research (CDC, 2007).

Concerningly, a high prevalence of falls in the home environment exists and falls also occur in in-patient hospital and rehabilitation settings (Teasell, McRae et al. 2002, Haines, Bennell et al. 2004). The fall incidence rate has been estimated at 7% within 7 days after a stroke (Indredavik, Ellekjaer et al. 2008), 25-37% up to 6 months after stroke (Kerse, Parag et al. 2008), 40 to 50% within a year (Belgen, Beninato et al. 2006) and at 55 to 73 after a year (Ashburn, Hyndman et al. 2008, Sackley, Brittle et al. 2008). Thus, efficacious balance support and training strategies are much needed for stroke patients and generally for individuals with impaired control of body balance.

In addition, occupational health workers ask for a sufficient manual handling tool. Nurses as well as physiotherapists are at risk for musculoskeletal injuries during manual patient handling activities such as patient transfer. Therefore the ACC New Zealand manual patient handling guidelines introduced a new LITEN UP approach (see figure 8, 9, 10) (ACC 2012).



A new approach to patient handling

- Lifting patients is one of the most significant causes of injury to nurses and carers. It costs the industry and ACC many millions of dollars each year and causes a great deal of suffering.
- Over recent years a new approach has been used overseas without outstanding results. However it requires a new way of thinking.
- We can eliminate thinking that a lift will be invoved in patient handling. Instead we can take an integrated approach towards risk assesment, handling patients, use of equipment and facility design.
- We call it the LITEN UP approach to patient handling. It sets a new best practice approach towards which all employers need to work. It‘s a major change–but one that has huge benefits for everyone.

Figure 8: The LIGHTEN UP approach.

Within this approach the ACC presents certain steps which they suggest for example for assisted walking with one or two carers.

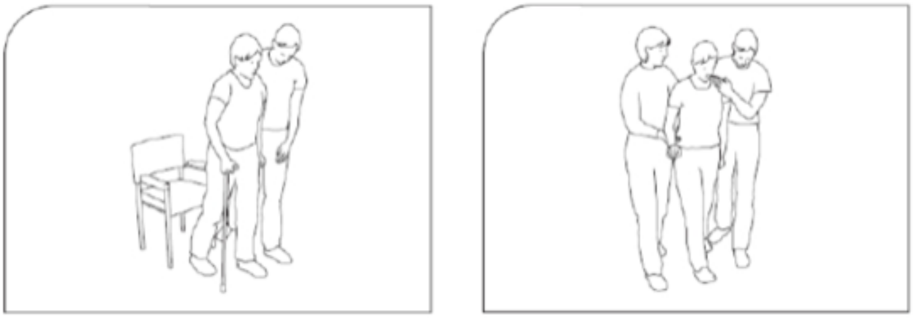
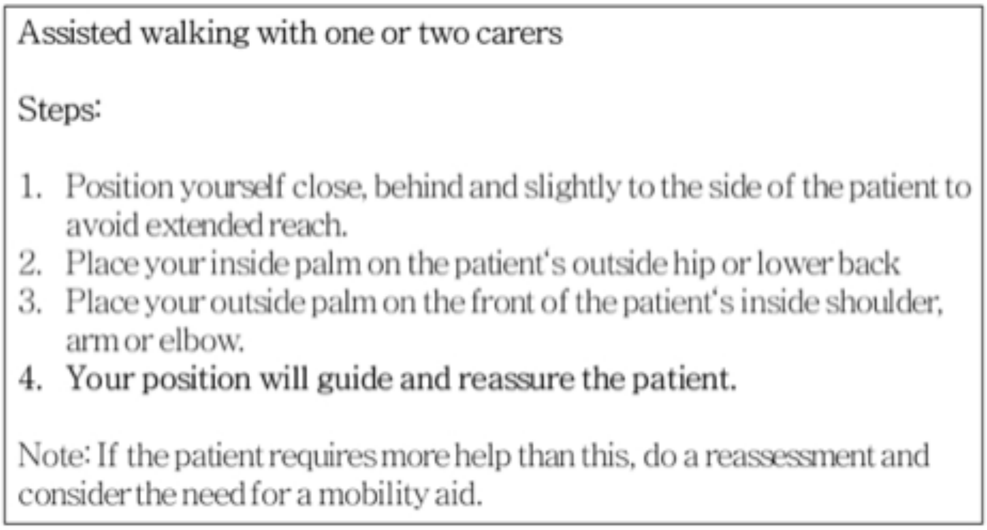


Figure 9: Coaching the patient to walk with a walking stick (right) and position for guiding the patient to walk (left).

Adapted from (ACC 2012).



Assisted walking with one or two carers

Steps:

1. Position yourself close, behind and slightly to the side of the patient to avoid extended reach.
2. Place your inside palm on the patient's outside hip or lower back
3. Place your outside palm on the front of the patient's inside shoulder, arm or elbow.
4. **Your position will guide and reassure the patient.**

Note: If the patient requires more help than this, do a reassessment and consider the need for a mobility aid.

Figure 10: Steps for therapists for assisted walking with patients with one or two careres.

Adapted from (ACC 2012).

The highlighted step number four “Your position will guide and reassure the patient” is a scarcely precise manual guidance advice for a caregiver in his or her daily work with a patient. With respect to the current work, the guidance part of this statement refers to the interpersonal coordination between caregiver and subject, such as leader follower relationships. Moreover, the reassurance part of the statement refers to the psychosocial effect of haptic interaction with light interpersonal touch for balance control.

For both balance impaired humans and clinicians who suffer from musculoskeletal health and mental issues, it is important to address the lack of empirical evidence for specific manual patient handling guidelines. It is important to find the trade-off between patient-caregiver safety and motor recovery. “If all ingredients for a good moving and handling culture are absent, the risk of a patient falling can also increase” (ACC 2012).

This dissertation attempts to contribute to fall prevention via the study of the provision of sensory information, particularly light haptic support during interpersonal coordination for control of body balance. The author believes it is necessary to study both caregiver as well as patient behavior in order to be able to incorporate the result into the complexity of balance rehabilitation for fall prevention.

In balance rehabilitation, physical therapists vary the provision of sensory cues, such as vision or surface compliance for balance training, to work on progress in motor learning and postural control (Muehlbauer, Roth et al. 2012). Haptic support during balance exercises can be seen as an interpersonal joint task between PT and patient. It challenges the patient’s balance performance when being supervised by the PT. We assume in doing so, PT and patient need to coordinate their movements. How this is actually implemented in applied balance rehabilitation remains to the best of our knowledge fairly scarce. In order to tackle this lack in balance rehabilitation research, we specifically examined the effects of light haptic support for control of body balance:

· firstly in healthy young individuals (study I) and

· secondly in elderly individuals with insecurities in control of body balance (study II).

In doing so, we aimed to

· firstly improve the understanding of interpersonal dynamics of light touch in general and,

· in the following, the caregiver-patient interaction during haptic support stabilization in particular.

Augmenting body balance with light interpersonal touch appears to be a promising strategy for balance rehabilitation. The question then arises as to how interpersonal clinician-patient interactions for balance support are actually implemented in balance rehabilitation. As this question is not only important for the implementation of an interpersonal light touch support strategy in general but also from a psychological theoretical point of view, the next chapter will attempt to introduce the ecological perspective on rehabilitation.

7 An ecological perspective on rehabilitation

This chapter introduces the theoretical background of this work, namely an ecological perspective on the perception of social affordances in clinical settings. An ecological perspective on rehabilitation

7.1 Professional expertise and patient handling skills

Although clinical guidelines and patient handling manuals provide descriptive models for caregiver behavior in routine clinical situations, such as physical support in patient transfer, empirical evidence for the efficacy and superiority of these behavioral models remains scarce. In addition, patient handling instructions are rarely described in fine-grained detail.

To our knowledge one of the better examples are the Accident Compensation Cooperation's New Zealand Patient Handing Guidelines (ACC 2012). The major aims of their 'LITEN UP' approach as stated in these guidelines are the reduction of patient handling risk mainly in terms of mechanical load imposed onto a caregiver as well as the promotion of physical independence of a patient in the rehabilitation process.

The later aim is especially interesting as it emphasizes potential therapeutic benefits. Light touch provision could reduce dependence on the caregiver and lead to reduced effort on behalf of the clinician. At the same time the patient would benefit from increased independence in the rehabilitation.

The specific technique this dissertation suggests is light interpersonal touch.

Besides finding an appropriate handling technique, the question of how caregivers actually learn to apply the optimal handling techniques is an interesting one.

One suggestion is by means of practical working experience, i.e. “ learning by doing.” Professional handling expertise improves patient safety and reduces physical risk for both parties. Internal models are suggested to influence handling experiences (Merfeld, Zupan et al. 1999). Independent of receiving education, clinicians might have the same experiences which form internal models. It can thus be deduced that practical handling in daily caregiver working life is a question of adequate education. More presumably working life of different job fields could be a question of an internal model.

7.2 Perception action coupling in clinical settings

To find out how caregivers learn to apply handling techniques, one must first ask: What are activators for our movements and how do we convey our behavior based on them? The perception of information is typically the start of an action. A person usually looks first where the key is then takes it (action is shaped by perception). Likewise, acting models the perception. For instance, when athletes are highly skilled at a particular activity because they practiced the action, such as throwing a football or hitting a baseball, a strong pairing between the perception and action (perception is shaped by the action) should exist. J.J. Gibson defined this phenomenon as the Perception-Action Coupling (PAC); a reciprocal communication of incoming sensory information and the creation of a suitable action (Warren 2006).

Assumingly, in clinical settings highly skilled caregivers (experts) should have tight coupling between the perception (e.g. detecting a fall) and action (e.g. physical support) based on practical working experience.

To further understand perception action coupling in interpersonal interactions, it helps to include the perspective of ecological psychology which tries to understand mind and behavior in a mechanistic way (Gibson 1987).
Gibson’s concept of affordances as opportunities for action that exists in the environment not resulting in behavior but simply making it possible, are fundamental in order to get an idea as to why humans act the way they do.
Why do caregivers really detect acute postural instability and the need for their adaptive handling support? When do they feel invited to act and what do their actions then look? According to Eleanor Gibson in *Where is the Information for Affordances* “what we perceive are the affordances of the world“ (Gibson E. J. 2000). She further explains in the just mentioned paper that the “environment provides resources or supports that we (may or may not) attend to and use. (Gibson E. J. 2000). Hence, the perception of events must be studied in order to be able to understand how affordances are perceived.
The properties of the environment and the actor create action possibilities (Withagen, de Poel, 2012).

In many clinical situations caregivers and patient are confronted with such action possibilities, for example during patient transfer or changing from sitting to standing or during balance exercises. It is in situations with various action possibilities that clinical guidelines should provide the clinicians with applicable aid which provides helpful orientation. A statement such as “Your position should guide and reassure the patient” as suggested by the ACC New Zealand patient guidelines is a start but is likely not doing a sufficient job. The information it adds is not enough in terms of valuable and practical information for applied balance rehabilitation.

7.3 The biopsychosocial model

The World Health Organization recommends an operationalized classification concept nemed as the International Classification of Impairment, Disability and Handicap (ICIDH). It provides a system for characterizing the needs of a patient in terms of requested sup- port on the grounds of the biopsychosocial model.
Criticism of the biomedical formulation put the WHO on the spot, hence, psychosocial factors were added to the biomedical model. This step was indispensable as until that point the biomedical model examined disease or injury as an entity entirely independent of behavior. At it’s best, the model exclusively explained behavior somatically. The abnormality (disease, injury) was concentrated conversely to the patient, from the biomedical point of view the biological component of behavior lies in its anatomical and physiological structures.

The prime request encouraging the addition of the psychosocial dimensions was that in a disease oriented model, such as the biomedical model, the caregiver possesses the most scientific understanding of the injury for which the patient came for treatment but not the most through and through scientific understanding of the patient who came in need for help. The patient meets the caregiver because of being out of function and not being able to perform goal oriented tasks e.g. activities of daily living (ADLs). The inability to function is labeled as maladaptive behavior and is considered a disability level. With the addition of the psychosocial component, the patient and not the injury was placed back into the caregiver agenda.

7.4 Ecological dynamic view on the biopsychosocial model

Function is defined as an interaction between the health condition in relation to individual (patient) and environmental (contextual) factors. Therefore, the ICF classification sees the health condition extrinsic to the patient and the environment.

Contrarily, ideas from ecological psychology to perception considered that function (adaptive behavior) is the degree of adaptation between the patient and the environment. The viewpoint presented from an ecological perspective is that function is intrinsically an emergence of the ability (inability) to establish specific relation with the environment under the constraints placed by the state of health/injury on the patient. Yet the ecological perspective integrates a different understanding of the environment than the ICF contextual factors.

To explicate, factors such as family caregiver information, copying strategies and contact information for therapist and other care providers related to support and relationship, are clearly important in rehabilitation but do not constitute the environment in terms of the ability of a patient to exploit to ecological information (in terms of specification of the environment) for performing actions.

In view of the ecological approach of perception action, coupling the environment encompasses patient surroundings such as the presence of another human (therapist) or objects, their surfaces and layouts in the treatment and at home. The natural environment and interpersonal human induced changes proposed as a sub-dimension under environmental contextual factors are not included in instructions or guidelines. These are characteristics of the ecological perspective.

To elaborate further and with an example, home modification provides the patient with affordances (possibilities for action) which, in order to be designed and encapsulated, the caregiver needs a basic understanding of the information patients detect from the environment. This specifies a particular therapeutic affordance for the regulation of behavior in a functional specific way. The concept of ecological information which specifies its environmental sources and the affordances for action comes into play.

7.5 The role of restoration and compensation in rehabilitation

The impairment-disability coupling is thought to be rather nonsensical. This preposition is justified by the statement that there is no one-to-one mapping from a disability to an impairment (behavior onto an impairment resembling a lesion or anatomical or physiological structure).

The physiological processes and anatomical structures are without a doubt of tremendous importance regarding behavior but they do not constitute behavior. In sum, various different movements from the body (and different sequences) are equivalent for the same act.

Central to the impairment-disability coupling is the motor behavior perspective. Consensus from motor control theories exists that motor programs or cognitive schemas (innate or learnt) are triggered or initiated by the CNS as responses originate from sensory inputs used for the construction and practice of a representation of the world.

In this respect psychological process establishes a meaning; it is never a fact in the world. Based on this, treatment objectives grounded on theory following a musculoskeletal injury are directed at restoring patient pre-morbid physical properties, such as muscle strength. The assumption is that once these physical prerequisites are “re-acquired” the CNS will trigger the correct motor program through a successful association process.

Applying the central theorem that the CNS actively constructs such a representation, J.J. Gibson argued in his approach that the environment is meaningful and directly perceived without the need for cognitive mediation (Gibson J. J. 1966). Contrary to theories in which entities mediate perception and action (internal models, mental representations), the ecological perspective commits to the idea that patients can achieve direct epistemic contact with the environment. Direct perception emphasizes the role of information embedded in the environment for the coordination and control of movement (Gibson J. J. 1966). During information movement coupling, action relevant informa- tion (e.g. visual, haptic) guides movement and movement, in return, is used to generate information de facto. By focusing on information sources patients are able to perceive affordances based on what the environment has to offer.

If information about the availability of affordances in the environment exists, then the patient's ability to detect and use that information for behavior regulation should have important ramifications in rehabilitation.

A major target of Gibson's ecological approach in clinical caregiver-patient interactions should be finding the information that points out therapeutic affordances. Ensuing,a treatment goal should be to teach patients strategies for making use of the available information in order to compensate and find ways relevant for finding ways to accomplish the activities for which help is needed.

Roger and colleagues describe the most common purposes of therapeutic touch, which often appear in combina- tion, as: assistive touch, caring touch, touch to provide and perceive information and touch used for intervention. Moreover, skilled used of touch is said to come from practi- cal experience rather than from formal training (Roger, Darfour et al. 2002). The necessity to experience different perceptual demanding interactions with patients, for example learning by doing, seems to be a key factor in order to strengthen the physiotherapists' prediction and skills and thus support the development to become an expert in his or her field.

Existing research relating to touch has so far mainly focused on patients' experience of touch regarding feeling (Henricson, Segesten et al. 2009). Observation relies strongly on the perceptual abilities of the observer (therapist) and is an active process which includes our own informational and organizational structure to process. It integrates the interplay between visual, haptic and acoustic cues. Thus, a general understanding of the nervous system, which is responsible for sensations, is crucial for the dialogue through touch in therapy. However, up to now this attribute has not yet been appropriately incorporated.

Touch is one of the therapist's principle distinguishing competencies. Three sensory systems are particularly well suited for the perception of interpersonal interactions: vision, auditory and particularly touch. Additional cues facilitating control of body balance, especially the haptic cue will play a role in the second study being performed for this dissertation (see chapter 10).

8 Experimental strategy

The methods used in the studies of this dissertation will be described in the following chapter.

8.1 Augmenting body balance using light interpersonal touch (study I)

The presented literature proposes two types of haptic support may be utilized to augment control of body balance (Fung and Perez 2011, Johannsen, Wing et al. 2012). One possibility to augment control of body balance is fixed light touch provision which serves as a spatial referent (Holden, Ventura et al. 1994). On the other hand, light touch provided by another human is thought to affect the postural control of a human partner (Johannsen, Wing et al. 2012) in an interpersonal balance task. In our first study (study I), passive light interpersonal touch was used in order to augment body balance. In addition, sensory feedback of both partners was manipulated. To the best of our knowledge, such a paradigm has not been tested in an interpersonal precision task in published literature to date (see chapter 9).

8.2 Active and passive interpersonal haptic support for balance support (study II)

Besides fixed haptic object support provision and as prviously mentioned, haptic support provision from another human partner can also be used in order to influence control of body balance. Moreover, the latter can be sub-classified into passive and active support conditions. To explicate, in the second study we define passive (facing away) light touch in the way that the tactile reference is provided to the contact receiver who is less involved in the haptic contact situation. Active (facing to) light touch implicates that the contact receiver is more involved in the provision of haptic support. Both haptic support conditions (active and passive) were applied in a clinical balance training situation. In addition, interpersonal forces between the partners were measured. To the best of our knowledge this kind of set up has not been tested in a clinical setting yet (see chapter 10).

8.3 Robotic light touch for balance support (study III)

The difficulty in using robots as therapists may be the full spectrum utilization of interpersonal coordination as human behavior may be difficult for the robots to simulate. Interpersonal cooperation is required to coordinate both the movements of the caregiver and the one of the patient. Marmelat and colleagues described the complexity of interpersonal coordination (Marmelat and Delignieres 2012) referring to Dubois' concept of weak and strong anticipation to explain this entanglement (Dubois 2003).

In regards to anticipation it stands for the synchronization of either an individual with its environment (finger tapping to a beat) or between two individuals. Three factors are emphasized by Keller and colleagues which affect interpersonal coordina- tion: adaptation, attention, and anticipation (Keller, Novembre et al. 2014). Specifically, anticipatory mechanisms allow individuals to plan their own movement with reference to predictions of time course of others' movements (Keller, Novembre et al. 2014). The ability to anticipate patients' movements is very important in order to prevent sudden loss of balance or even falls in balance therapy with balance impaired individuals. In reference to robotic light touch support in study III, to the best of our knowledge, no research has yet been conducted to investigate robotic methods in this particular manner.

Thus, to facilitate study I and to continue the idea of providing balance support in an interpersonal light touch context, study III investigates light touch provided by a caregiver, such as a human therapist or through robot touch. The rationale behind this experiment lies in the question whether robot and human can provide similar tactile feedback to another human in order to support control of body balance during MFR. In addition to study I, study III is intended to present a comparison of human and robot as feedback light touch providers and their effectiveness in reducing postural sway. The challenge for the robotic solution was to adapt or anticipate patients' movement while providing a light touch for tactile feedback.

9 Study I: Interpersonal interactions for haptic guidance during maximum forward reaching

In the following the first study (study I) will be presented starting with a general introduction, followed by methods, results and a discussion of the findings. The author of this dissertation is the first author of this publication and played the decisive role in planning, executing and writing up study I.

9.1 Publication I

The first publication for this cumulative dissertation is called „Interpersonal interactions for haptic guidance during maximum forward reaching.“ It was published in the international scientific journal Gait and Posture.

9.2 Introduction

The overall objective of this study was to enhance the knowledge on interpersonal light touch actions. We aimed to better understand how the interactionists make use of haptic cues. To this end, the sensory feedback availability of both partners was manipulated. In doing so, the contact provider's visuotactile interpersonal context was controlled as well as the contact receiver's access to additional haptic feedback other than the interpersonal light finger contact from the contact provider. Environmental (sensory cues) were manipulated in a dynamic interpersonal joint precision task, such as the maximum forward reach.

9.3 Jornal confirmation for publication

The international scientific journal Gait and Posture gave permission to use the publication for this dissertation.

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Full length article

Interpersonal interactions for haptic guidance during maximum forward reaching

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ABSTRACT

Caregiver–patient interactions rely on interpersonal coordination (IPC) involving the haptic and visual modalities. We investigated in healthy individuals spontaneous IPC during joint maximum forward reaching. A 'contact-provider' (CP; n = 2) kept light interpersonal touch (IPT) laterally with the wrist of the extended arm of a forward reaching, blind-folded 'contact-receiver' (CR; n = 22). Due to the stance configuration, CP was intrinsically more stable. CR received haptic feedback during forward reaching in two ways: (1) presence of a light object (OBT) at the fingertips, (2) provision of IPT. CP delivered IPT with or without vision or tracked manually with vision but without IPT. CR's variabilities of Centre-of-Pressure velocity (CoP) and wrist velocity, interpersonal cross-correlations and time lags served as outcome variables. OBT presence increased CR's reaching amplitude and reduced postural variability in the reach end-state. CR's variability was lowest when CP applied IPT without vision. OBT decreased the strength of IPC. Correlation time lags indicated that CP retained a predominantly reactive mode with CR taking the lead. When CP had no vision, presumably preventing an effect of visual dominance, OBT presence made a qualitative difference: with OBT absent, CP was leading CR. This observation might indicate a switch in CR's coordinative strategy by attending mainly to CP's haptic 'anchor'. Our paradigm implies that in clinical settings the sensorimotor states of both interacting partners need to be considered. We speculate that haptic guidance by a caregiver is more effective when IPT resembles the only link between both partners.

1. Introduction

Balance control requires successful integration of self-motion information from multiple sensory modalities [1]. The human postural control system is able to derive self-motion not only from its primary motion detectors but also from actively acquired or passively received light skin contact with the environment [2,3]. Haptic information also stabilizes quiet stance when it originates from a non-weight-bearing contact that possesses motion dynamics of its own, i.e. another human (interpersonal touch; IPT) [4]. Deliberately light IPT is intended to involve small forces only, in order to minimize the mechanical coupling and to maximize the informational exchange [5]. Sway reductions with IPT may emerge from mechanically and informationally coupled adaptive processes and responsiveness in both partners [5].

When joint action partners coordinate their movements they may share information but also face differences in task-relevant knowledge and roles. For example, a blind person receives tactile, visual or verbal cues from the guiding partner. Spontaneous interpersonal postural coordination (IPC) has been demonstrated in diverse joint tasks [6]. For example, implicit observation of a partner in a joint precision task improved manual performance as well as IPC [7]. Verbal communication in a joint problem solving task also influences IPC regardless of whether visual information about the partner was available [8], perhaps mediated by shared speaking patterns [9]. Finally, haptic interactions provide powerful sensory cues for IPC [10]. Coordinative processes supporting goal-directed joint action can result in the emergence of spontaneous leader-follower relationships, for example in a visual, periodic collision avoidance task [11]. In situations such as quiet stance IPT, however, no clear leader-follower relationship has been reported, also not in situations with asymmetrical stance postures with one person intrinsically more stable than the partner [4,12,13].

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A well-established clinical task to assess body balance control is the Functional Reach (FR) [14]. Maximum forward reaching (MFR) challenges the control of body sway as the body's Centre-of-Mass (CoM) approaches the physical limits of stability so that the likelihood of balance loss increases with reaching distance [15]. We assumed that joint action in an asymmetric interpersonal postural context, such as the MFR task with one partner more intrinsically stable, would be more adequate than quiet stance to investigate spontaneously emerging leader-follower relationships. According to the ecological principles of interpersonal affordances [16], we aimed to create dependencies between two individuals by asymmetries in the intrinsic postural stability and in the knowledge of the joint postural state based on the available sensory feedback. We expected that additional haptic feedback, for example as either an additional object or IPT, would increase reach distance but also stabilize body sway in the reaching person (contact-receiver; CR). Further, we anticipated that spontaneous IPC, specifically the leader-follower relationship, is altered by the haptic feedback available to CR as well as by the visual feedback available and the instructions given to the person providing IPT (contact-provider; CP). Although CR would be the main actor performing the MFR, we assumed that CR would become more dependent on CP, when CP was able to perceive the scene.

2. Methods

2.1. Participants

Twenty-two healthy participants (average age = 26.3 yrs, SD = 4.1; 17 females and 5 males; all right-handed for writing) were tested. Participants with any neurological or orthopaedic indications were excluded. Two naïve, healthy young adults provided IPT

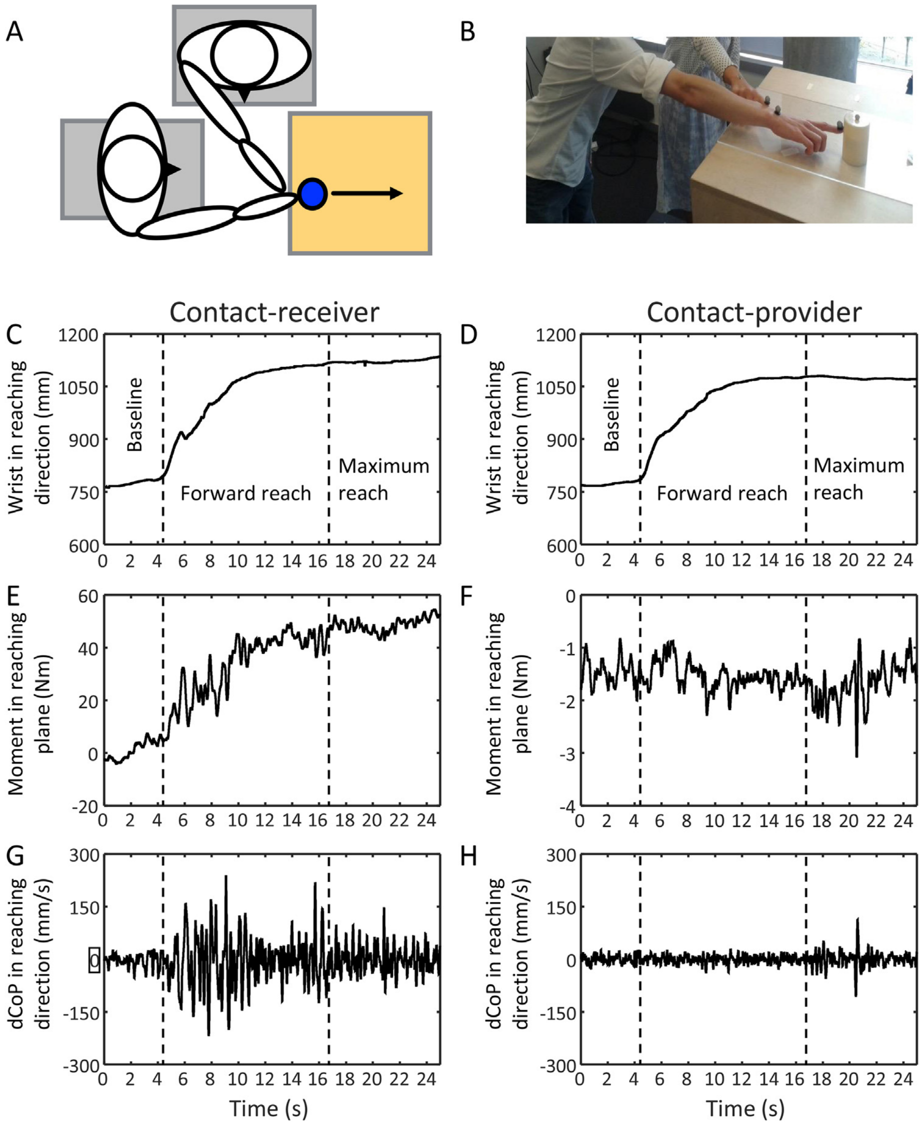

Fig. 1. (A) The stance configuration of the experimental setup at the beginning of a trial. Upon a signal by the experimenter the contact receiver will start the forward reach pushing the object as far out as possible. (B) The contact provider keeping light contact with the receiver's wrist. (C) Position of a receiver's wrist in the reaching direction across single trial. The dashed lines indicate the beginning and end of the forward reach phase. (D) Position of a providers's wrist in the reaching direction across the same trial. (E) Moment in the plane parallel to the reaching direction exerted by the receiver. (F) Corresponding moment exerted by the provider. (G) Receiver's Centre-of-Pressure (CoP) velocity in the reaching direction. (H) Corresponding CoP velocity of the provider.

to all CRs. Participants were recruited as an opportunity sample from students of the university. The study was approved by the local ethical committee and all participants gave written informed consent.

2.2. Experimental procedure

Six conditions were combined from the task requirements imposed on CR and CP. CR stood blindfolded on a force plate in bipedal stance to perform MFR with or without tactile feedback at the fingertips by touching a light object (OBT; weight = 59.3 g). CR was instructed to reach as far forward as possible or asked to shove OBT instead, which was placed upon a fibreglass plate (kinetic coefficient of friction = 0.33). OBT could move in any direction and therefore afforded manual precision. Before the start of a trial, CR was instructed to stand in a relaxed manner, the dominant right arm extended at shoulder height to reach horizontally above a table. The table was adjusted to each individual to avoid surface contact.

CP stood orthogonally to CR in bipedal stance on a force plate placed ahead of CR in the reaching direction (Fig. 1a) and provided light IPT during CR's reach with the right extended index finger contacting CR's medial wrist (Fig. 1b). The visuotactile interpersonal context (VIC) consisted of three conditions: IPT with open or closed eyes and CP tracking the motion of CR's wrist with the extended index finger visually but without IPT. Before the start of a single trial, CP kept his contacting finger close to the wrist of CR waiting for the specific task instructions.

Each condition was assessed in blocks of 10 trials for a total of 60 trials in fully randomized order. A single trial lasted 25 s consisting of three phases: baseline (5 s static posture), self-paced forward reaching (cued by experimenter) and reach end-state (static posture until trial end).

Two force plates (Bertec 4060H, OH, USA; 600 Hz) oriented in parallel measured both individuals' six components of the ground reaction forces and moments to calculate anteroposterior (AP) and mediolateral (ML) components of the Centre-of-Pressure (CoP). In addition, a four-camera motion capture system (Qualisys, Göteborg, Sweden; 120 Hz) tracked markers on both individuals at the following locations: right index finger, right wrist, left and right shoulders, 7th cervical segment.

2.3. Data reduction and statistical analysis

Motion data were spline interpolated to 600 Hz and subsequently merged with the kinetic data. Time series data were smoothed using a generic dual-pass, 4th-order Butterworth lowpass filter (cutoff = 10 Hz). After differentiation, trials were segmented into three movement phases based on the AP position of CR's wrist marker (Fig. 1c). Reach onset was determined as the first frame that exceeded 4 standard deviations of wrist position within the initial 3 s. Stop of forward reaching was determined as the velocity zero-crossing closest to 95% of the absolute maximum reach distance. Reach performance was analysed in the horizontal plane. Average reach amplitude, direction, curvature (normalized path length = path length/straight line length) of the trajectory from baseline position to maximum reaching end-state as well as the average and standard deviation of reaching velocity were extracted. Velocity information is the predominant source for body sway control [17], therefore postural control in the maximum reach end-state was extracted as the standard deviation of CoP velocity (SD dCoP) in both directions (Fig. 1g). Similarly, standard deviation of the wrist velocity (SD dWrist) expressed reaching stability and precision in both directions. For each phase, IPC was estimated in terms of the cross-correlation function (time lag range: ±3 s) between both participants' moments as recorded by the force plates in the plane parallel to the reaching direction (Fig. 1e–f). The largest absolute cross-correlation coefficient and corresponding time lag were extracted. Coefficients were Fisher Z-transformed for statistical analysis. Two-factorial repeated

Table 1
Statistical effect table. OBT: light object; IPT: interpersonal touch; ML: mediolateral; AP: anteroposterior; n.s.: not significant; Italics: marginal significance. P-values are rounded to two or three decimals respectively.

	Condition		Presence of OBT	Visuotactile interpersonal context	Interaction between OBT and visuotactile interpersonal context
	Interpersonal contact		No IPT	IPT	IPT
Trial phase	Parameter		$F_{1,21}$; p; partial η^2	$F_{2,42}$; p; partial η^2	$F_{2,42}$; p; partial η^2
Reaching performance					
Forward reaching	Horizontal amplitude		4.80; 0.04; 0.19	n.s	n.s
	Directional angle		n.s	n.s	n.s
	Horizontal velocity		19.67; 0.001; 0.48	n.s	n.s
	Variability of horizontal velocity		12.87; 0.002; 0.38	n.s	n.s
	Curvature		n.s	n.s	n.s
Control of body balance and posture					
Reach end-state	Variability of wrist velocity	ML	n.s	n.s	n.s
		AP	14.56; 0.001; 0.41	n.s	3.59; 0.04; 0.15
	Variability of CoP velocity	ML	36.50; 0.001; 0.64	n.s	n.s
		AP	13.65; 0.001; 0.39	*2.95; 0.06; 0.12*	n.s
Interpersonal postural coordination					
Complete trial	AP wrist	Coefficient	4.49; 0.05; 0.18	11.64; 0.001; 0.36	n.s
		Time lag	n.s	n.s	n.s
	AP moment	Coefficient	6.45; 0.02; 0.24	n.s	n.s
		Time lag	n.s	n.s	3.84; 0.03; 0.15
Forward reaching	AP wrist	Coefficient	6.75; 0.02; 0.24	10.40; 0.001; 0.33	n.s
		Time lag	n.s	5.34; 0.01; 0.20	3.55; 0.05; 0.15
	AP moment	Coefficient	13.21; 0.002; 0.39	n.s	n.s
		Time lag	n.s	n.s	n.s
Reach end-state	AP wrist	Coefficient	n.s	9.69; 0.001; 0.32	n.s
		Time lag	4.25; 0.05; 0.17	n.s	n.s
	AP moment	Coefficient	n.s	4.63.; 0.02; 0.18	n.s
		Time lag	n.s	n.s	n.s

measures ANOVAs with OBT (2 levels) and VIC (3 levels) as within-subject factors were calculated. Significant findings were detected at a Greenhouse-Geisser-corrected $p < 0.05$.

3. Results

Table 1 presents the statistical results for all extracted parameters.

3.1. Forward reaching performance

Fig. 2a shows the amplitude of CR's reach as a function of the VIC and OBT presence. Without OBT the amplitude of reaching was 37.9 cm (SD = 7.0). OBT increased reach distance to 38.9 cm (SD = 6.5). The average reach direction indicated a slight medial deviation of 5.9° (SD = 7.0). Horizontal wrist velocity was reduced from 46.5 mm/s (SD = 19.2) to 40.9 mm/s (SD = 17.8) with OBT. Likewise, the variability was reduced from 54.2 mm/s (SD = 26.5) to

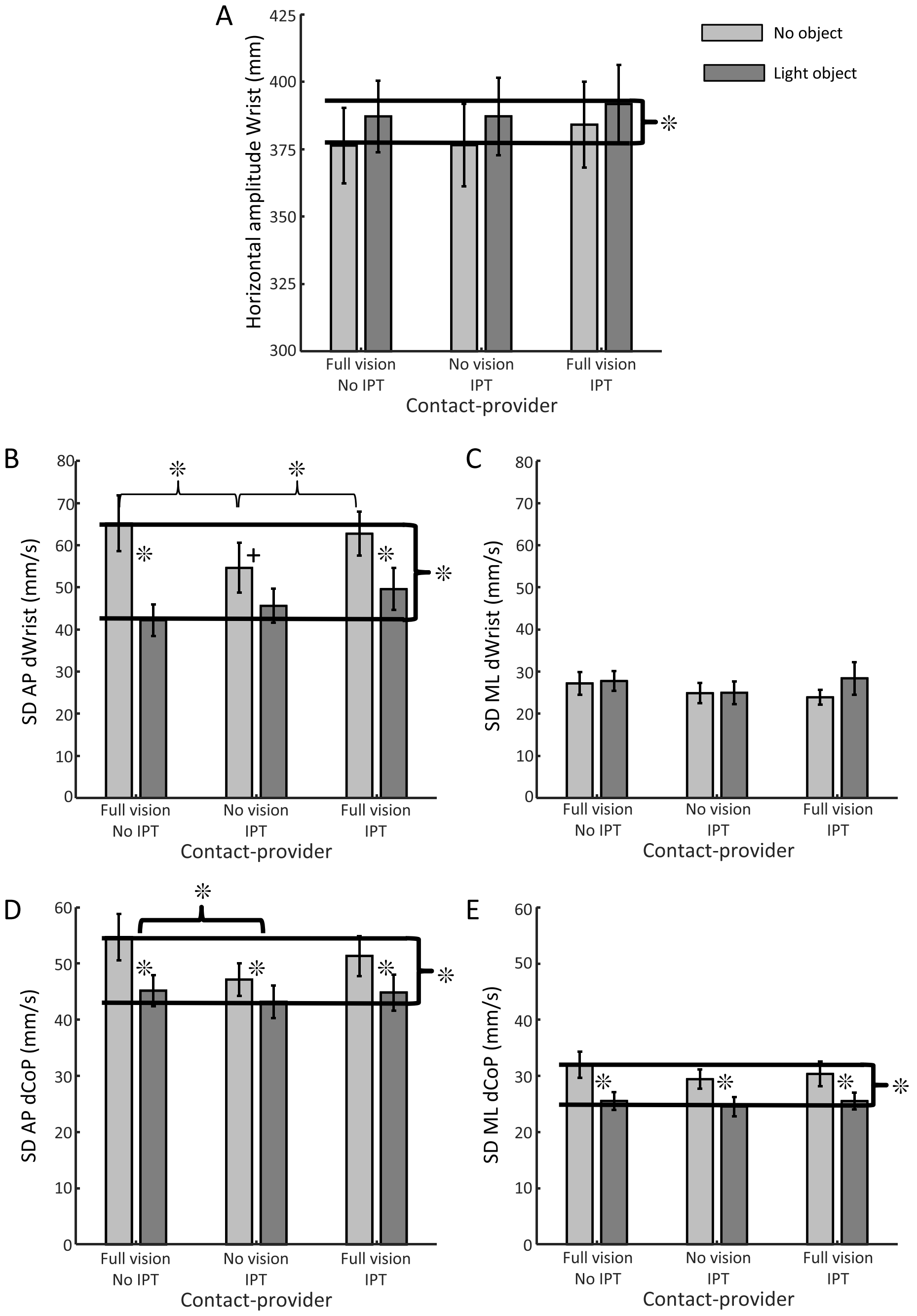

Fig. 2. (A) The horizontal amplitude of the contact receiver's wrist as a function of the presence of the light object (OBT) and visuotactile interpersonal context. The standard deviation of the contact receiver's wrist velocity in the anteroposterior (B) and mediolateral (C) directions during the reach end-state. The standard deviation of the contact receiver's CoP velocity in the anteroposterior (D) and mediolateral (E) directions during the reach end-state. Bold vertical brackets indicate an effect of OBT presence. Bold horizontal brackets indicate a single comparison between visuotactile interpersonal contact conditions averaged for the OBT factor. Thin horizontal brackets refer to a single comparison between not-averaged specific visuotactile interpersonal context conditions. Error bars indicate the between-subject standard error of the mean. The asterisk indicates $p < 0.05$ and the cross indicates $p < 0.1$. IPT: interpersonal touch.

42.5 mm/s (SD = 14.4) with OBT. Curvature indicated a slightly curved trajectory (average = 1.7, SD 0.8), which was not affected by OBT or VIC.

3.2. Postural control in the reach end-state

The reach end-state lasted on average 10.4 s (SD = 3.0). Separating wrist velocity into its AP and ML components resulted

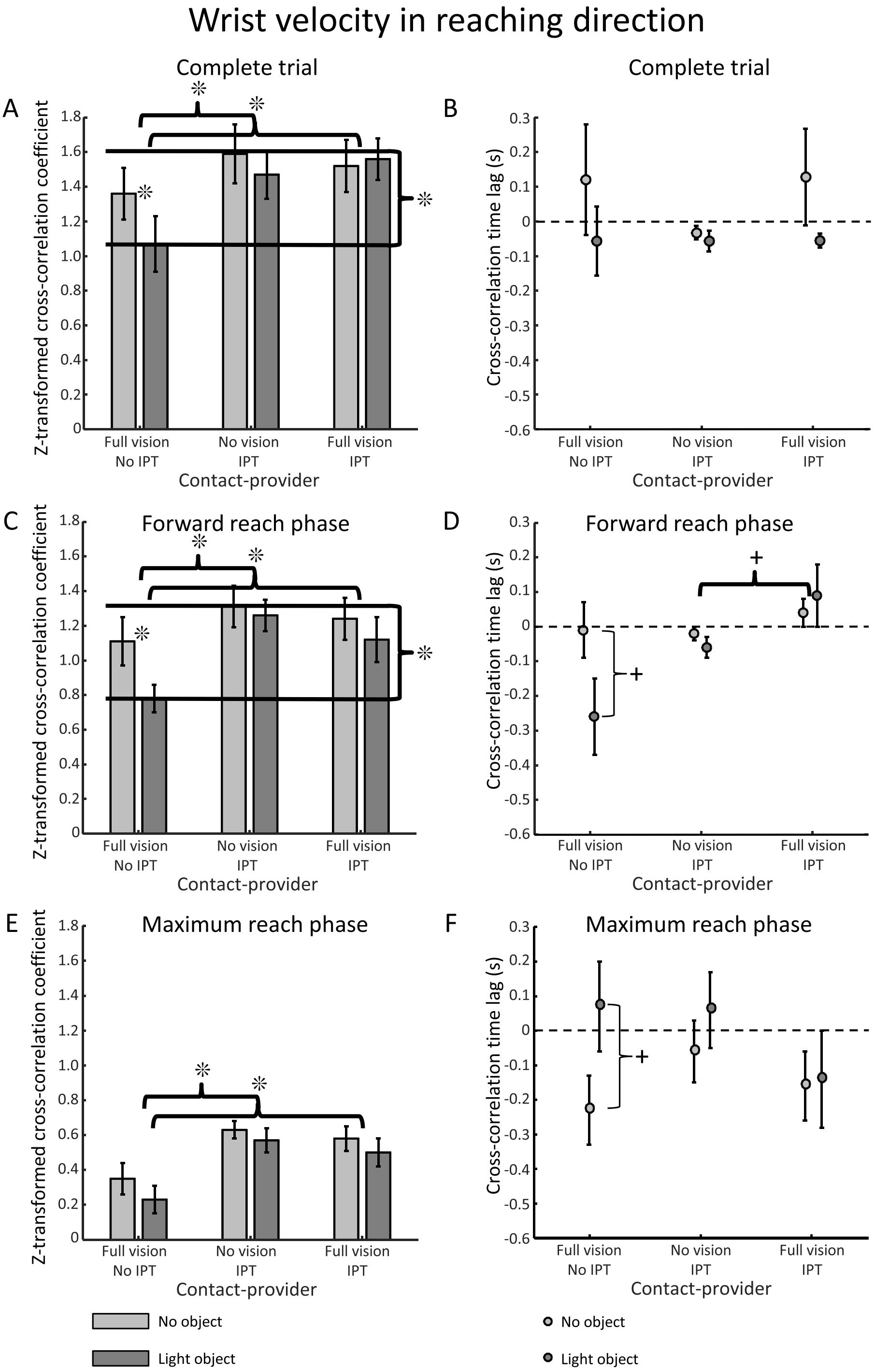

Fig. 3. Left panels show the average Fisher Z-transformed cross-correlation coefficients of the wrist velocity in reaching direction as a function of the presence of the light object (OBT) and visuotactile interpersonal context in (A) the complete trial, (C) reaching phase and (E) maximum reach end-state. Right panels show the cross-correlation time lags as a function of the visuotactile interpersonal context and the object presence in (B) the complete phase, (D) reach phase, (F) and maximum reach end-state. Bold vertical brackets indicate an effect of OBT presence. Bold horizontal brackets indicate a single comparison between visuotactile interpersonal contact conditions averaged for the OBT factor. Thin horizontal brackets refer to a single comparison between not-averaged specific visuotactile interpersonal context conditions. Error bars indicate the between-subject standard error of the mean. The asterisk indicates $p < 0.05$ and the cross indicates $p < 0.1$. IPT: interpersonal touch.

in an effect of OBT and an interaction between OBT and VIC on AP SD dWrist. OBT reduced AP SD dWrist in general (Fig. 2b). Post-hoc single comparisons indicated that IPT without visual feedback and without OBT resulted in a reduction compared to the other two VIC conditions (Fig. 2b).

SD dCoP was reduced by the presence of OBT in both directions (Fig. 2d–e). A tendency of an effect of VIC was found in the AP direction. Single comparisons showed that the IPT condition with visual feedback reduced SD dCoP compared to visual tracking.

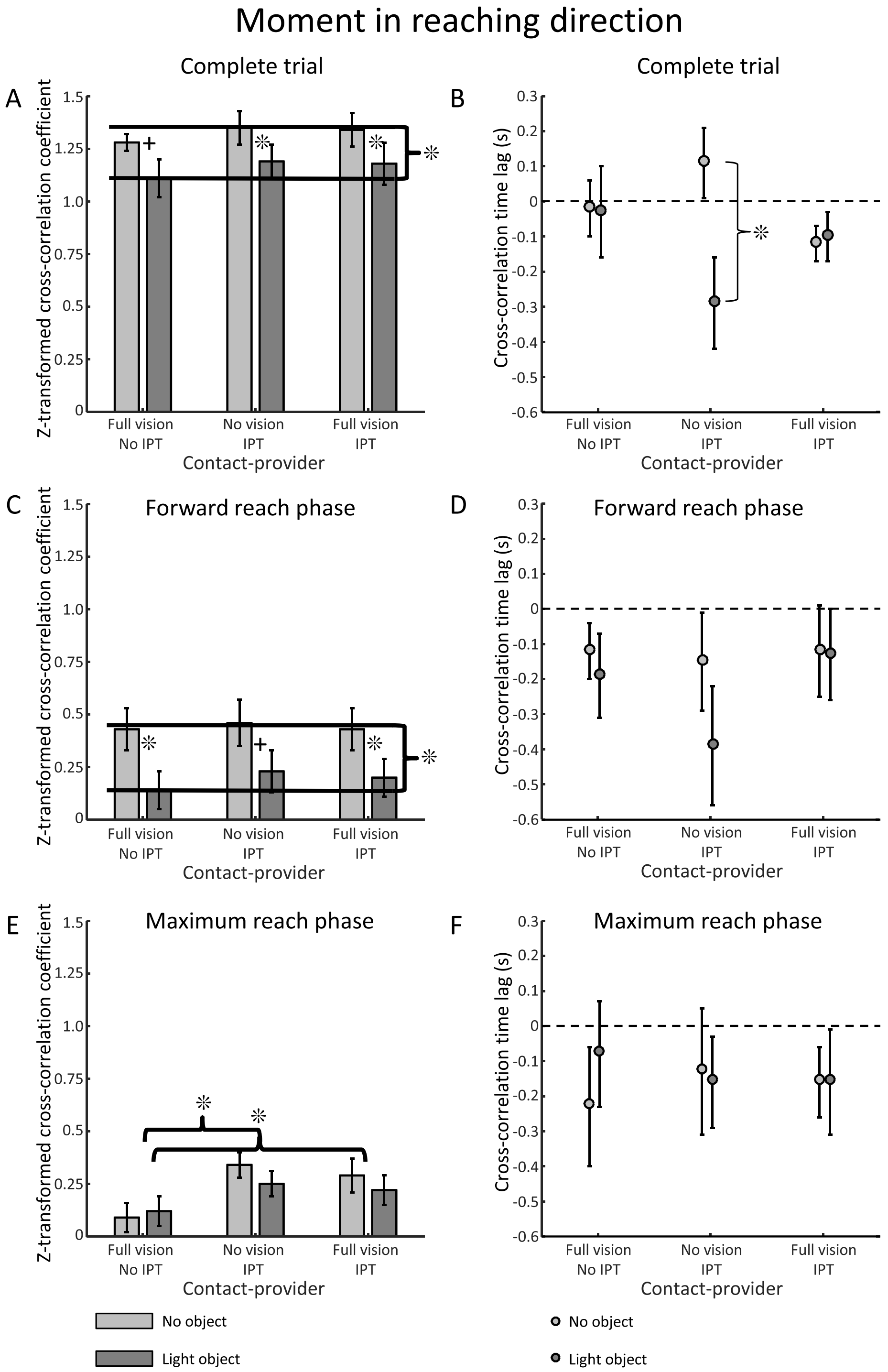

Fig. 4. Left panels show the average Fisher Z-transformed cross-correlation coefficients of the moments in reaching direction as a function of the presence of the light object (OBT) and visuotactile interpersonal context in (A) the complete trial, (C) reaching phase and (E) maximum reach end-state. Right panels show the cross-correlation time lags as a function of the visuotactile interpersonal context and the object presence in (B) the complete phase, (D) reach phase, (F) and maximum reach end-state. Bold vertical brackets indicate an effect of OBT presence. Bold horizontal brackets indicate a single comparison between visuotactile interpersonal contact conditions averaged for the OBT factor. Thin horizontal brackets refer to a single comparison between not-averaged specific visuotactile interpersonal context conditions. Error bars indicate the between-subject standard error of the mean. The asterisk indicates $p < 0.05$. IPT: interpersonal touch.

3.3. Interpersonal coordination

Fig. 3 shows the Fisher-Z-transformed coefficients and time lags of the peak cross-correlations between the wrist velocities of CR and CP in the reaching direction for the complete trial (Fig. 3a–b), the forward reaching (Fig. 3c–d) and the reach end-state (Fig. 3e–f).

Across the complete trial, both OBT and the VIC affected the strength of IPC (Fig. 3a). Single comparisons indicated that in visual tracking, coefficients were weakest compared to the other two IPT conditions. Time lags tended close to zero (average = 8 ms, SD = 457; Fig. 3b). In the forward reaching, coefficients were lower compared to the complete trial but affected in a similar manner (Fig. 3c). The time lags were affected by the VIC and showed an interaction with OBT. Single comparisons indicated that in the condition with IPT and visual feedback, CP tended to show a slight lead ahead of CR (average = 69 ms, SD = 338) compared to IPT without visual feedback, where the interpersonal relationship tended to be reversed (average = 41 ms, SD = 115). In visual tracking, OBT tended to result in CP lagging behind CR by about 263 ms (SD = 528; Fig. 3d) in contrast to a zero lag without OBT (average = 10 ms, SD = 397). In the reach end-state, visual tracking resulted in the weakest IPC compared to the two conditions involving IPT (Fig. 3e). The time lags showed an effect of OBT presence with OBT resulting in zero lags (average = 6 ms, SD = 595) compared to a lead by CR when OBT was absent (average = 151 ms, SD = 454; Fig. 3f).

Fig. 4 shows the Fisher-Z-transformed coefficients and corresponding time lags of the peak cross-correlations between CR and CP for the moments in the plane parallel to the reaching direction across the complete trial (Fig. 4a–b), forward reaching (Fig. 4c–d) and in the reach end-state (Fig. 4e–f).

OBT decreased the strength of IPC (Fig. 4a). Regarding the time lags, single comparisons showed that an interaction between OBT and VIC was caused by the presence of OBT to alter the interpersonal timing when CP provided IPT without vision (Fig. 4b). With OBT, CP followed CR by 286 ms (SD = 62), while in the absence of OBT, CP was 112 ms (SD = 486) ahead of CR. In the other two VIC conditions time lags showed a lead of CR about 70 ms (SD = 400). In forward reaching, coefficients were generally lower relative to the complete trial. Similarly, OBT presence reduced the strength of IPC (Fig. 4c). Time lags indicated that CP followed CR by about 184 ms (SD = 614; Fig. 4d). In the maximum reach phase coefficients were still lower than during forward reaching. An effect of VIC was found (Fig. 4e). Single comparisons indicated that visual tracking showed the weakest IPC compared to the other two conditions. Overall, the time lags averaged around 155 ms (SD = 697; Fig. 4f).

4. Discussion

We aimed to understand the spontaneous IPC for balance support in maximum forward reaching and intended to modulate the leader-follower relationship by creating asymmetric interpersonal dependencies. CR, deprived of visual feedback and in the less stable postural state, was supposed to rely more strongly on CP when no alternative source of haptic information was available. On the other hand, CP's responsiveness to CR was expected to vary with the visuotactile interpersonal context in terms of visual feedback and the IPT instruction.

OBT influenced the reaching performance of CR. The precision demands (speed/accuracy) were greater with OBT as expressed by CR's reduced and less variable reaching speed. In the reach end-state, increased amplitude with OBT (Fig. 2a) coincided with reduced AP wrist and SD dCoP (Fig. 2b,d). Our results confirm previous observations that a target object in the FR task facilitates performance [18,19]. Despite low friction of the fibreglass surface, the interaction with OBT could have resulted in haptic feedback at the fingertips facilitating control of balance [3] and resembling a non-rigid, haptic 'anchor' as conceptualized by Mauerberg-deCastro and colleagues [20].

Contact between the hands ought to have resulted in better interpersonal coordination and synchronization. Indeed, an increase in strength of IPC between the hands occurred in the two IPT conditions. Nevertheless, mechanical coupling between the hands is unlikely as IPT provided support to CR's arm in terms of vertical friction only. The absence of an effect of the VIC on SD dWRI in the ML direction indicates that IPT did not constrain CR's forward reaching. This is corroborated by the observation that the movement trajectories were also not influenced by IPT. In contrast in the reach end-state, both AP wrist and CoP velocity showed selectively reduced variability during IPT without visual feedback. For SD dCoP this difference was independent of the presence of OBT (Fig. 2d). It seems that the benefit of IPT appeared predominantly when CP was not able to observe CR visually. Summation of OBT and IPT should have resulted in greatest improvements in reach distance and balance stability. The lack of a summation effect of the two haptic modes [21] as observed in individual, passively received light touch [22] suggests that the two sources were not integrated. Reliability estimates or the contextual information of the two sources could have been too divergent [23]. While CR participants have experience in contacting environmental objects during stance, the social content of IPT could have made it incompatible with the OBT signal. Perhaps the variability reductions with IPT may result from social facilitation [24] with the requirement that CP attends exclusively to CR's local dynamics.

Individuals achieve joint goals by switching between symmetrical and asymmetrical modes of IPC depending on the constraints of their complementary roles. Skewes et al. [25] investigated how people trade synchronization and complementarity in a continuous joint aiming task. Interestingly, when the level of difficulty in the complementary task became too high for one partner of the dyad, this person became less adaptive to their partner's requirement thus taking the 'leader' role in the joint task. In addition, partners synchronized better with an irregular, but adaptive partner, than with a completely predictable one [25]. OBT presence and the VIC altered the strength and temporal coordination between both individuals during IPT across the complete trial and during forward reaching. OBT reduced the cross-correlation coefficients between both individuals (Figs. 3a, 3c, 4a, 4c). OBT was more relevant to CR than to CP, therefore this difference expresses CR's responsiveness to the interpersonal context. For example, being engaged in a precision task, restricted CR's adaptability, which could explain why CR was 'leader' in the majority of testing conditions.

With respect to IPC of the postural responses, CP used to follow CR's motion by up to 200 ms when visual feedback was involved (Fig. 4b,d). Thus, visual processing in CP's task requirements seems to have resulted in a reactive mode. While the nature of the IPT signal is local, with eyes open CP may have attended to the global scene and involuntarily experienced visual dominance [26]. Although vision dominates in bisensorial contexts, latencies to visual stimuli in these situations are typically delayed compared to touch or audition [27]. In the condition without visual feedback for CP but constant IPT, the presence of OBT made a big difference (Fig. 4b). Removing OBT, which deprived CR of a competing tactile signal, seems to have caused CR to a focus on the IPT signal, thereby turning CP into the 'leader'. During forward reaching (Fig. 4d), however, once more time lags indicated CP as the 'follower'. Naturally, the reaching phase did not contain the transition points such as initiation and stop. It is reasonable that these two events are central to successful IPC. Perhaps, in the IPT condition without visual feedback and in the absence of OBT at CR's fingertips, CR's motion onset was triggered by CP.

According to our present results, a caregiver needs to take into account the context-dependent responsiveness of a patient. If a caregiver intends to guide a patient haptically, the caregiver needs to ascertain that two prerequisites are met: the patient has no competing tactile signal available and the therapist deliberately refrains from adopting a reactive mode based on vision. This still needs to be tested in realistic patient-caregiver settings.

5. Conclusions

We described the effects of visual and haptic sensory information on interpersonal postural coordination in an asymmetrical maximum forward reach joint action paradigm. We observed temporal movement coordination between a 'contact-provider' and a 'contact-receiver' to depend on the presence of an external object and the visuotactile interpersonal context. Interpersonal postural coordination was strongest when deliberately light IPT was provided without the presence of an additional object at the contact-receiver's fingertips. As the leader-follower relationship between both partners was also modified by the visuotactile interpersonal context of the contact-provider, the sensorimotor states of both partners have to be considered of equal importance. We speculate that IPT is a promising strategy for patient guidance in clinical settings. More research is needed before its implementation as a patient manual handling tool.

Conflict of interest

There are no conflicts of interest for any of the authors.

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10 Study II: Interpersonal interactions for haptic guidance during balance exercises

In the following the second study (study II) will be presented. Starting with an introduction, followed by methods, results and discussion. This study was an international collaboration between the University of Pittsburgh, Carnegie Mellon University in Pittsburgh and TUM. The author of this dissertation is the first author of this publication and played the decisive role in planning executing and writing up study II.

10.1 Publication II

The second publication for this cumulative dissertation is called „Interpersonal interactions for haptic guidance during balance exercises." It was published in the international scientific journal Gait and Posture. The international scientific journal Gait and Posture gave permission to use the publication for this dissertation.

10.2 Introduction

The overall aim of this study was to enhance the understanding of interpersonal light touch dynamics in caregiver-patient interactions for balance stabilization in particular. The main objective was to better understand the spontaneous interpersonal coordination for balance support in a clinical setting. Since studies which have focused on fall prevention show balance training to be a promising factor to reduce imbalance and fall risk (Barnett, Smith et al. 2003) study II investigated interpersonal coordination during balance exercises. The creation of natural intersensory conflicts by concurrently allowing different sets of sensory cues is successfully used to stimulate intersensory reorganization as a training approach (Borstad, Bird et al. 2013). Hence, a PT can increase the difficulty of balance exercises by decreasing proprioception, visual information, or by changing the base of support in order to challenge a subject's postural stability. One of the aims of this study was to better understand how different levels of balance exercise difficulty affect IPC between a PT and a client. To this end, six different balance exercises with increasing difficulty were used in this study II. External human support is a form of haptic support for balance control. This kind of support, especially during balance exercises, can be seen as an interpersonal haptic form of communication between PT and client.

During this communication, we assume that coordination of movements between the PT and client occurs. How interpersonal interactions for haptic support are actually implement- ed in balance rehabilitation remains unknown to the best of our knowledge. Thus, another aim was to understand the interpersonal communication between a PT and client during balance exercises. Environmental sensory cues (surface, head movement, vision) as well as subject related constraints (elderly individuals with balance insecurities) and the inherent task factor (increasing difficulty level of balance exercises) were manipulated in a dynamic interpersonal balance rehabilitation task, such as balance exercises.

10.3 Jornal confirmation for publication

The international scientific journal Gait and Posture gave permission to use the publication for this dissertation.

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Interpersonal interactions for haptic guidance during balance exercises

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ABSTRACT

Background: Caregiver–patient interaction relies on interpersonal coordination during support provided by a therapist to a patient with impaired control of body balance.

Research question: The purpose of this study was to investigate in a therapeutic context active and passive participant involvement during interpersonal support in balancing tasks of increasing sensorimotor difficulty.

Methods: Ten older adults stood in semi-tandem stance and received support from a physical therapist (PT) in two support conditions: 1) physical support provided by the PT to the participant's back via an instrumented handle affixed to a harness worn by the participant ("passive" interpersonal touch; IPT) or 2) support by PT and participant jointly holding a handle instrumented with a force-torque transducer while facing each other ("active" IPT). The postural stability of both support conditions was measured using the root-mean-square (RMS) of the Centre-of-Pressure velocity (RMS dCOP) in the antero-posterior (AP) and medio-lateral (ML) directions. Interpersonal postural coordination (IPC) was characterized in terms of cross-correlations between both individuals' sway fluctuations as well as the measured interaction forces.

Results: Active involvement of the participant decreased the participant's postural variability to a greater extent, especially under challenging stance conditions, than receiving support passively. In the passive support condition, however, stronger in-phase IPC between both partners was observed in the antero-posterior direction, possibly caused by a more critical (visual or tactile) observation of participants' body sway dynamics by the therapist. In-phase cross-correlation time lags indicated that the therapist tended to respond to participants' body sway fluctuations in a reactive follower mode, which could indicate visual dominance affecting the therapist during the provision of haptic support.

Significance: Our paradigm implies that in balance rehabilitation more partnership-based methods promote greater postural steadiness. The implications of this finding with regard to motor learning and rehabilitation need to be investigated.

1. Introduction

Falls and fall related injuries in older adults are a public health issue [1,2]. Balance exercises, however may reduce falls risk [3]. In balance rehabilitation, a physical therapist (PT) manipulates the provision of sensory cues during sensorimotor training to facilitate motor learning, and control of body balance [4–6].

The factors governing sensorimotor interactions between therapist and client, however are poorly understood [7]. Interpersonal sensorimotor interaction can be classified into cooperation and collaboration [8]. In contrast to collaborative interactions that do not integrate a priori role assignments, roles are assigned a priori to each participant in cooperative interactions. For example during balance exercises, this can lead to an allocation of sub-tasks, such as provision of haptic balance support by a therapist and reception by the client involved in the balancing task [9].

Additional tactile feedback is a reliable approach to augment control of body balance [10]. In the traditional paradigm ("active" light touch), a participant is controlling the upper limb directly, which is contacting the external haptic reference [11]. Hereby, the movement degrees of freedom of the contacting limb are used for precision control of the contact force with the control of body sway as a separate process [12]. In addition to the haptic feedback signal, the output of fingertip control could serve as a signal to control sway [13]. In non-manual,

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"passive" light touch, the contact is delivered to a participant's body segment. A participant is less able, to control the precision by which the contacting force is applied [13]. Here, the movement degrees of freedom available to a participant for controlling the contact force are limited by the current postural degrees of freedom, thereby creating a direct equivalence between control of body sway and precision of the contact.

Passive light touch with an earth-fixed reference results in proportional sway reductions in the range of 20%–30% [13]. This is similar to what has been reported in studies involving fingertip light touch [i.e. 14]. Interpersonal fingertip touch (IPT) leads to lesser sway reductions of around 9–15% [9,14–17]. The reason for this diminished effect could lie in the fact that the contact reference is not earth-fixed but shows own motion dynamics, which might make disambiguation of the haptic signal in terms of own sway-related feedback more challenging. Johannsen et al. [9] assessed "passive" IPT in neurological patients as well as chronic stroke and reported sway reductions between 15%–26%. In stroke patients, passive, trunk-based IPT [9], nevertheless, seemed more beneficial than fingertip IPT [16].

In our study, we directly contrasted the effects of active and passive support modes on body sway in a therapeutic setting. We measured the interaction forces between a physiotherapist and participants and characterized the interpersonal postural coordination (IPC) between both partners. We predicted that the participant would demonstrate the greatest sway reductions when passive IPT was provided to the trunk with no involvement in contact precision control. We increased the sensory challenges imposed by the balance task (foam surface, eyes closed, pitch head movement) and assumed that with increasing difficulty, the benefit of IPT would increase as well potentially in interaction with the specific IPT mode.

2. Methods

2.1. Participants

Ten older adults without significant neurological or orthopedic history, between the age of 71 and 86 years (mean age 79 yrs, SD = 5; 5 females, 5 males; all right-handed for writing) participated in this study. One PT (16 years of experience) provided support.

2.2. Recruitment and exclusion criteria

Participants were recruited from a sample of screened healthy elderly subjects from a preliminary study [18]. This study was approved by the Institutional Review Board of the University of Pittsburgh.

2.3. Demographic data

Participants completed the Activities-specific Balance Confidence Scale (ABC) questionnaire [19] and the Functional Gait Assessment [20] prior to the experiment. The participants reported a balance confidence level between 74% and 100% (mean 94%, SD = 8). The Functional Gait Assessment (FGA) is a modification of the Dynamic Gait Index (DGI) that uses higher level gait tasks [20]. Participants achieved scores between 17 and 30 in the FGA (mean 26, SD = 5).

2.4. Experimental design

Participants performed 2 sets of 6 randomized balance exercises during two different conditions: passive support (PS) and active support (AS) (Fig. 1). In the PS condition, the PT who was in bipedal stance with full vision, stood behind the participant and lightly held on to an instrumented handle mounted on the back of the participant's vest and applied stronger support only when he felt the participant required firmer assistance to maintain upright balance. In the AS condition, the PT and the participant faced one another and simultaneously held on to the handle. Participants were instructed to stand as stable as possible with their arms crossed in front of their waist (PS) or to stand as stable as possible while holding on to a handle (AS). For each set of six balance conditions participants completed a partial factorial design of the conditions (see Fig. 1D). These exercises were chosen across a range of difficulty based on a preliminary study [18].

2.5. Instrumentation

The participant and PT stood on separate force platforms (Bertec, Columbus, Ohio, USA) that measured ground reaction forces and moments at a sampling rate of 120 Hz (see Fig. 1A and B). A tri-axial load cell (DSA-03 A TecGihan, Japan) was mounted to a custom-made handle and bracket which was secured to the back of a support vest worn by the participant to measure forces during the PS condition (see Fig. 1A). Force plate and load cell data were collected by the same data acquisition system (National Instruments, Austin, TX). During the AS condition, the handle was removed from the vest and a second handle was attached to the bracket for the participant's use (see Fig. 1B).

2.6. Procedure

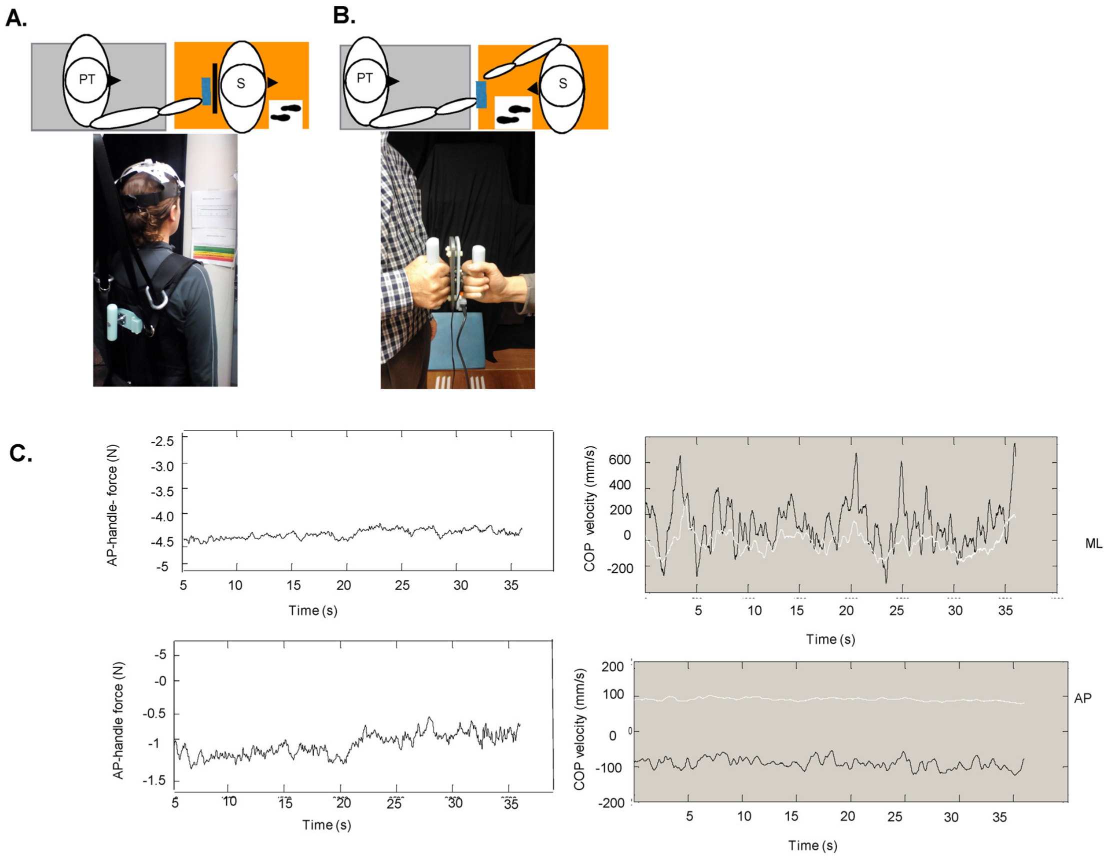
Participants stood in semi-tandem stance by placing their feet so that the medial borders were touching, and moving their dominant foot backward by a half of foot length [21]. During the foam surface conditions, participants stood on foam (AIREX Balance Pad S34-55, height 6 cm, length 51 cm, width 40 cm). During the pitch condition, participants moved their head over a total range of 30 degrees at 1 Hz by following a metronome [22]. Trials lasted 30 s and participants wore a safety harness.

2.7. Data reduction and statistical analysis

The force platform and load cell data were transformed into center of pressure (COP) and handle force measurements, respectively, using calibration equations The antero-posterior (AP) and medio-lateral (ML) components of the COP and the AP component of the handle force were extracted. All data time series were smoothed using a dual-pass, 4th order Butterworth lowpass filter (cutoff = 10 Hz). COP data were numerically differentiated to produce COP velocity measures. Velocity information is the predominant source of body sway control [23] therefore the root-mean-square of the AP and ML COP velocity (RMS dCOP) were the primary postural control measures. The IPC was estimated by computing the cross-correlation functions between both participants' COP velocity time series.

Cross-correlations were computed within a range of minimum and maximum time lags between ± 3 s. We used the standard MATLAB cross correlation function which measures the dependence between two signals [24,25]. The largest maximum (in-phase behavior) and minimum (anti-phase behavior) cross-correlation coefficients and corresponding time lags were extracted. The cross-correlation coefficients were Fisher Z-transformed for statistical analysis.

SPSS version 23 was used for statistical analysis. A linear mixed model analysis with support mode (2 levels: active and passive) and condition (6 balance exercises) effect as well as the support * condition interaction was performed. For the estimation of the model we used a maximum likelihood method. Postural sway parameters (RMS) were analyzed including subject as a random effect while IPC parameters (correlation coefficients, lags) and forces were analyzed using only fixed effects. A diagonal covariance structure was used for repeated effects in the mixed model [26]. An alpha level of 0.05 was used for level of significance, and post-hoc comparisons were computed using Sidak adjustment.



D.

	Surface	Vision	Head movement
1.	firm	eyes open	still
2.	firm	eyes closed	still
3.	firm	eyes closed	pitch
		Break	
4.	foam	eyes open	pitch
5.	foam	eyes closed	still
6.	foam	eyes closed	pitch

Fig. 1. (A & B) The stance configuration of the experimental setup at the beginning of a trial with the physical therapist on the grey force plate and the subject in semi-tandem on the orange force plate in the passive intermittent support mode (A) and in the active continuous support mode (B). The instrumented handle is represented by the blue rectangle in the schematic. Time series plots of the antero-posterior (AP) handle force (left) and AP and medio-lateral (ML) COP velocity of the physical therapist (light) and subject (dark) in active support mode during a foam surface, eyes closed and pitch movement trial (right) (C). The subject performs six balance exercises with increasing difficulty (D) (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

3. Results

3.1. Postural control

3.1.1. Sway velocity in AP direction

Significant support (F (1,58.5) = 22.8, $p < 0.001$) and condition (F (5,28.5) = 80.6, $p < 0.001$) effects were found for participant RMS dCOP in the AP direction (Fig. 2). The passive support led to higher sway velocity production. The sensory conditions generated progressively increased sway velocity (see Fig. 2A).

3.1.2. Sway velocity in ML direction

Analysis of the RMS dCOP in the ML direction generated similar support (F(1,57.5) = 51.3, $p < 0.001$) and condition (F (5,25.9) = 59.2, $p < 0.001$) effects as in the AP direction, but there was also a significant interaction between condition and support (F (5,25.8) = 3.90, p = 0.001) (Fig. 2B). The interaction indicates that there was greater difference in the amount of sway velocity between

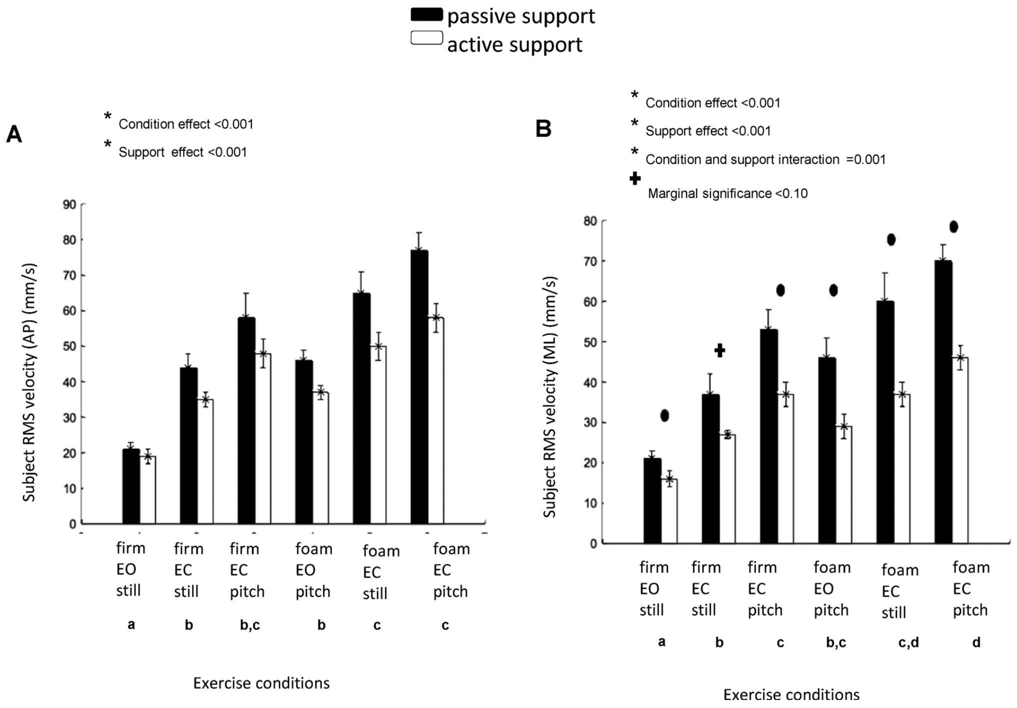


Fig. 2. The RMS COP velocity as a function of the exercise conditions and the support provision (passive/active) in AP (A) and in ML direction (B). Letters show the pairwise comparison between conditions; the same letters express conditions are not significantly different from each other. Bold dots indicate the significant support differences within each condition. Error bars indicate the standard error of the mean.

passive and active support conditions as the balance conditions became more challenging. The difference in sway velocity ranged from approximately 18.5 mm/s in the firm surface, eyes open, head still condition to 58 mm/s during the foam surface, eyes closed, head pitch condition.

3.2. *Handle forces*

3.2.1. *Average AP handle force*

A significant effect of support mode (F(1,46.2) = 8.22, p = 0.01) on the average handle force was found (Fig. 3A). A mean force of 1.7 N (SD 0.5 N) in the posterior direction on the handle was observed during the passive support trials. During the active support trials, the forces of the PT and participants counteracted one another on average, with a mean force of 0.01 N (SD = 0.05 N) towards the PT. A significant effect of sensory condition (F(5,22.2) = 4.0, p = 0.01) was found. Larger posterior forces on the handle were exerted during the foam, eyes closed, and passive support conditions compared with much smaller force exertion during the other conditions. During the active support trials, a pattern emerged in which the force was directed toward the participant in the easier conditions, and toward the PT in the foam, eyes closed conditions. Lateral forces were also minimal (see Fig. 3A).

3.2.2. *Variation in AP handle force*

The magnitudes of variation of handle forces applied between the PT and participant, as measured by the standard deviation of the time series, are shown in Fig. 3B. A progressive increase in variation in forces occurred as the sensory conditions became more difficult (F(5, 21.8) = 18.4, $p < 0.001$).

3.3. *Interpersonal coordination of postural sway*

3.3.1. *Minimum cross correlation coefficients between participant and PT*

Fig. 4 displays the minimum (i.e. anti-phase) cross correlation coefficients between the COP velocity of the PT and participant. A significant condition effect was found in both the AP (Fig. 4A, F (5,29.7) = 9.2, $p < 0.001$) and ML directions (Fig. 4B and F(5, 37.1) = 3.9, p = 0.01). In the AP direction, IPC anti-phase behavior was larger in the eyes closed conditions. In the ML direction, there was less anti-phase IPC in the firm surface, eyes open, head still condition.

3.3.2. *Maximum cross correlation coefficients between participant and PT*

The maximum (i.e. positive) cross-correlations were greater in absolute magnitude than the minimum (negative) cross-correlations, indicating that the in-phase IPC was more prominent than the anti-phase IPC. The IPC in-phase behavior of the COP velocity in the AP direction demonstrated significant support, condition and interaction effects (Fig. 4C). Lower average interpersonal cross-correlation coefficients were found in AS 0.28 (SD 0.02) than in PS 0.34 (SD 0.02) in the AP direction (F(2,101.8) = 13.4, $p < 0.001$), which indicated greater strength of the in-phase IPC in the passive mode. The sensory conditions differed (F(5,34.2) = 20.8 $p < 0.001$), which showed increasing IPC during the more difficult sensory conditions, similar to the pattern of results of the RMS dCOP. A significant interaction between support and exercise mode (F(5,34.2) = 2.7 p = 0.04) demonstrated greater IPC during the active support mode for the firm surface, eyes open, head still condition, in contrast with greater IPC during the passive support mode for all other conditions. The in-phase coordination in the ML directions showed a significant condition effect only (F(5,35.8) = 14.24 $p < 0.001$).

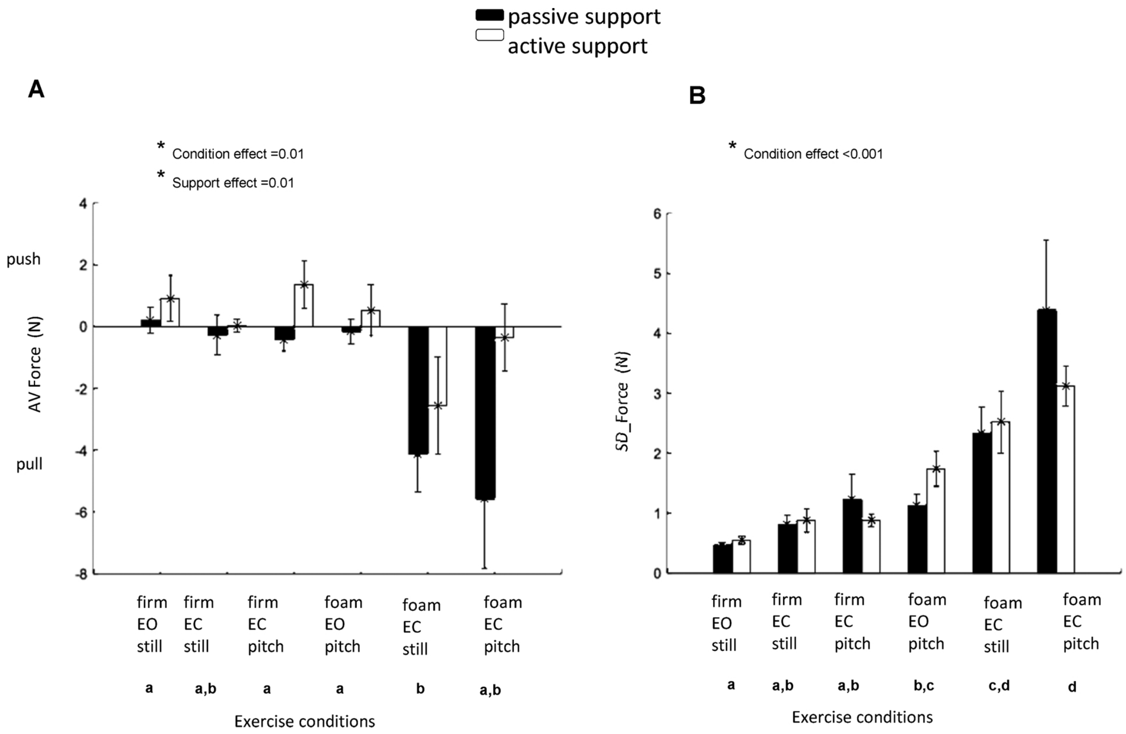


Fig. 3. The average (AV) of the handle force as a function of the exercise conditions and the support mode (passive/active) (A) as well as the standard deviation (SD) of the handle force as a function of the exercise conditions and the support mode (passive/active) (B). Letters show significant pairwise differences between conditions; same letters express that conditions are not significantly different from each other. Error bars indicate standard error of the mean.

3.4. Time lags in IPC between participant and PT

We found a significant support mode effect (F(1,90.6) = 6.6, p = 0.02; passive mean = −287 ms SD = 13 ms; active mean = 210 ms SD = 13 ms) (Fig. 5A; anti-phase IPC). The PT led in all but the third sensory condition (AS) and followed in all but the second and third sensory conditions (PS). Fig. 5C (in-phase IPC) demonstrates a pattern in which the PT was always the follower (AS: mean = 159 ms SD = 17 ms; PS: mean = 323 ms SD = 21 ms) with the exception of the easiest sensory condition (firm, EO, still) in active mode.

4. Discussion

We aimed to contrast the effects of two different modes of client participation in the provision of interpersonal light touch balance support by a therapist to balance-challenged older adults.

4.1. Postural control

In both directions, the active support mode resulted in less participant sway velocity compared with the passive support mode. Proportional sway velocity difference between both modes was 32% of passive condition, which is similar to passive LT sway reductions with an earth-fixed reference or fingertip LT [14,27]. An interaction between support mode and sensory condition for sway in the ML direction indicated that the active support mode provided a greater benefit with greater sensory disruption. The observation that more active participation in the control of contact force precision resulted in reduced sway under conditions of greater sensorimotor destabilization was unexpected as in previous studies the comparative proportional benefit of passive trunk-based IPT on body sway tended to be greater than IPT at the fingertips.

The difference between the two IPT modes in this study could rest on stronger and less ambiguous haptic feedback from the grasp of the handle or processes of anticipatory postural control and voluntary force precision control in the active IPT mode. Wing et al. [28] investigated the coupling between grip force during one-handed precision grasp on a manipulandum and concurrent postural adjustments in anticipation of dynamic and static loads during horizontal pulling and pushing. They demonstrated a functional linkage between grip force adjustments anticipating changes in load force on the manipulandum and ground reaction torque in anticipation of self-imposed balance perturbations due to the pushing and pulling motion. They suggested that an efferent signal controlling grip force could facilitate the prediction of upcoming postural load and appropriate postural adjustments [28]. Further, minimization of the interaction force and its variability could have resembled the goal of a so called “suprapostural” task resulting in proactive, task-adapted body sway reductions [29,30]. As the latter mechanism might apply to fingertip IPT too, we speculate that an efferent grip force control signal contributing to anticipatory postural control facilitated postural stability primarily in this study instead.

By facing the participant in active mode, the therapist might have received clearer social cues about postural destabilization of the participant that facilitated internal simulation of a participant’s sway dynamics for the anticipation of instabilities and need for support [31]. For example, the sight of another person can improve an individual’s ability to compensate for imbalance [32].

4.2. Handle forces

It needs to be considered that in the passive IPT mode, strength of the contacting force was upregulated intermittently based on the therapist’s visuotactile assessment of a participant’s current state of postural stability. In the easier sensory conditions, the interaction forces remained relatively low, which possibly indicates the relative absence of active stabilization of participants’ sway by the therapist. The

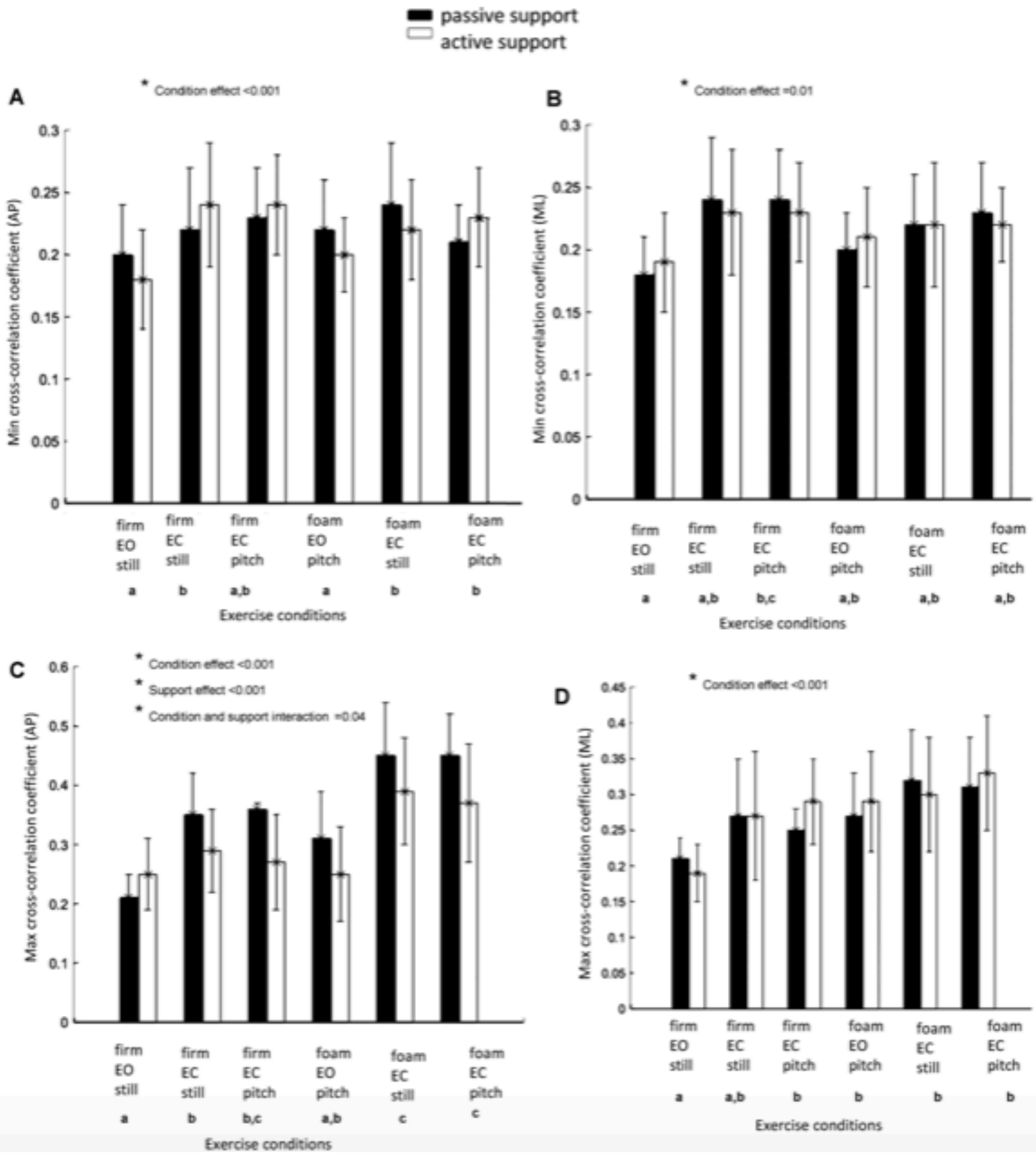


Fig. 4. Upper panels show the average minimum cross-correlation coefficients of the CoP velocity as a function of the exercise conditions and the support mode (passive/active) in AP (A) and ML (B) direction. Lower panels show the average maximum cross-correlation coefficients of the CoP velocity as a function of the exercise conditions and the support mode (passive/active) in AP (C) and ML (D) direction. Statistical results refer to the Z-transformed cross-correlations. Minimum cross-correlations represent negative values and are shown rectified for better visual understanding. Error bars indicate the standard error of the mean. Letters show significant differences between conditions; same letters express conditions that are not significantly different from each other.

Interaction forces fell into the range from 4N to 6N in the two most challenging conditions (foam surface), which could imply more continuous in addition to stronger haptic support.

Nevertheless the stronger haptic support with passive IPT did not result in less variable body sway compared to the active mode in the two most challenging conditions. As the variability of the interaction force was comparable, we can ascertain that the average interaction forces are not affected by an averaging artefact of extreme values.

Despite less physical support by the therapist, the balance reduction is still greater in the active mode, which corroborates our conclusion that participants received additional cues facilitating of body sway.

control.

4.3. Interpersonal coordination of postural sway

In the AP direction of sway spontaneous in-phase in both active and passive IPT was the prominent IPC pattern, which confirms observations in previous studies [14,15]. IPC was strongest in the two most hallenging sensory conditions and in the majority of sensory conditions passive IPT resulted in stronger IPC than active IPT, with the exception of the easiest condition. Possibly, active stabilization of the participant by the therapist was applied less frequently in the easiest

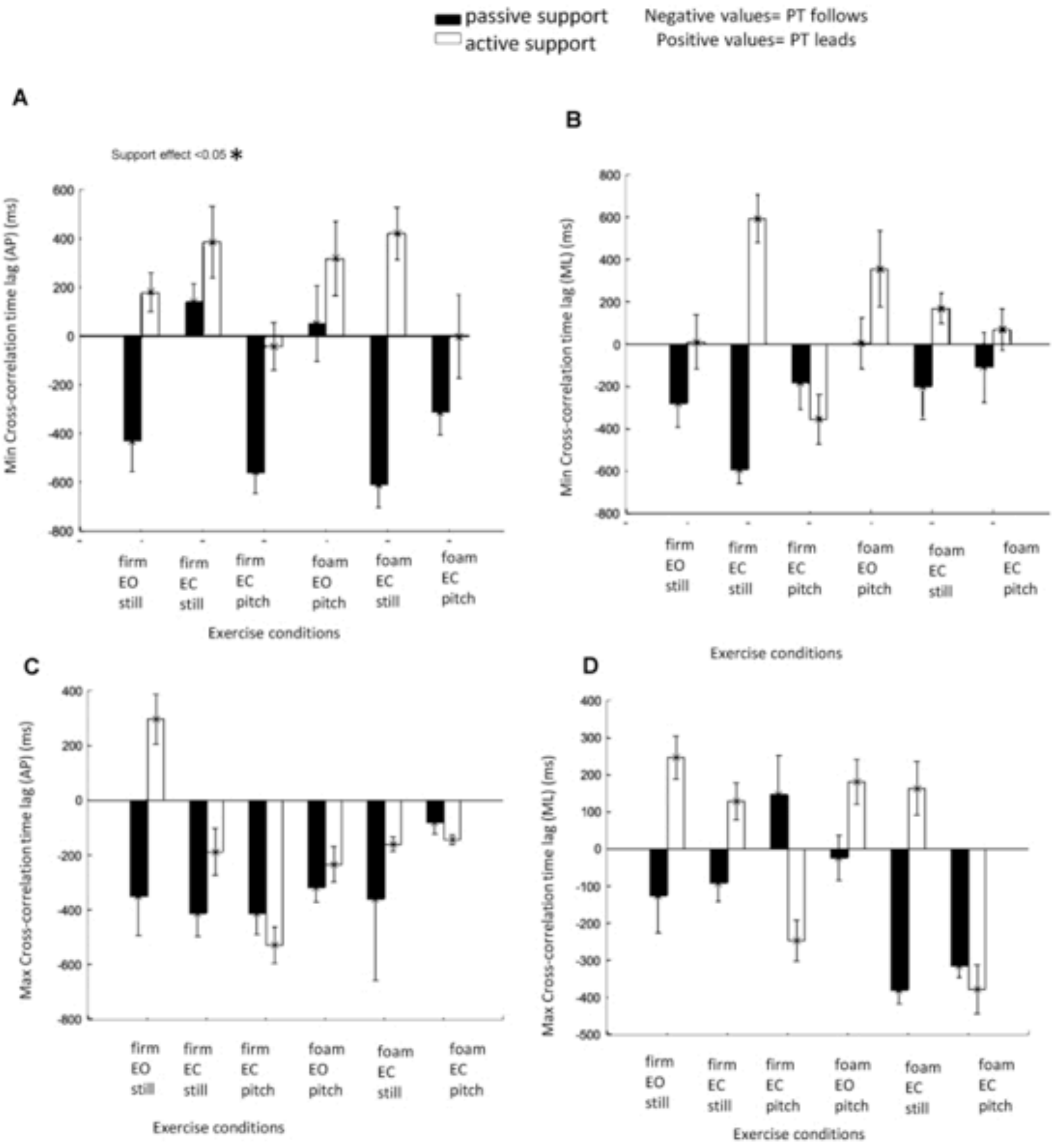


Fig. 5. Upper panels show the minimum average cross-correlation lags of the CoP velocity as a function of the presence of the exercise conditions and the support mode (passive/active) in AP (A) and ML (B) direction. Lower panels show the maximum average cross-correlation lags of the CoP velocity as a function of the presence of the exercise conditions and the support mode (passive/active) in AP (C) and ML (d) direction. Statistical results refer to the Z-transformed cross correlations. Error bars indicate the standard error of the mean.

sensory condition with passive IPT, therefore causing weaker IPC, compared with the active IPT mode, in which stronger interpersonal entrainment [33] could have driven IPC. Fingertip IPT has been reported to result in lower cross-correlation coefficients compared to shoulder IPT [17], which might indicate that the involvement of a greater number of movement degrees of freedom in both partners interpersonal haptic interactions amounts to generally weaker IPC.

The corresponding time lags of the maximum in-phase cross-correlation coefficients demonstrated an average lead of 164ms by the participant's over the therapist's body sway fluctuations. This is surprising as previous studies reported zero lags [14,17,34]. In these studies, however, visual feedback of the partner's body sway was not available or restricted to peripheral vision, which could have allowed haptic feedback to dominate the IPC. In this current study, the therapist kept open eyes permanently to observe a participant's body sway. We speculate, that visual dominance caused the therapist to automatically adopt a reactive follower mode [35,36]. We observed a similar leader-follower relationship in a forward reaching task, when visual feedback was available to the contact provider [37].

5. Conclusion

We described the effects of passive and active involvement for balance support in a therapeutic context. The passive mode demonstrated increased strength of the interpersonal coordination and the active mode decreased the postural sway of the participant to a greater extent.

We suggest balance training could be more effective when both partners face each other. Being more involved in the interaction might enable the participant to spend more time in a challenging balance si- tuation searching and practicing a successful postural strategy. This still needs to be further investigated.

Conflict of interest

There are no conflicts of interest for any of the authors. Acknowledgements

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11 Study III: Effects of robotic haptic assistance on human postural control during maximum forward reach

In the following, the third (study III) will be presented. The author likes to emphasize that this dissertation can only present an outlook of this study.

Study III was an interdisciplinary collaboration between the Chair of Human movement Sciences and the Department of Electrical and Computer Engineering at the Technical University of Munich. It consists of two experiments: KUKA I and KUKA II.

The author of this dissertation only designed and performed experiment KUKA I, interpreted the results and wrote part of the paper.

11.1 Introduction

The general objective was the translation of interpersonal coordination for light tactile balance support into a robotic solution. The rationale behind this experiment lies in trying to answer the question of whether a robot can provide tactile feedback similar to human interpersonal light touch to another human partner for control of body balance.

Elderly patients are prone to diseases and injuries that cause sudden loss of vestibular function with the loss in latter being mainly due to decrease in blood supply which causes balance loss and falls (Konrad, Girardi et al. 1999). Postural recovery in older individuals is attentionally demanding and for older adults with poor balance undertaking a second task may contribute to falls.

Brauer and colleagues conducted a dual task paradigm where the person stood firmly planted on a moving platform and as a second task had to provide verbal reactions to auditory tones, which showed balance recovery in elderly with balance impairment was more difficult compared to a healthy person (Brauer, Woollacott et al. 2001). This suggested that postural instability could contribute towards falls.

Fall risk is also very high in patients with neurological disorder, such as stroke. Falling is a major complication in such patients. Nyberg et al. reported 62 (39%) of stroke patients suffered falls and most of them occurred during transfers or from sitting in a wheelchair. Also, 4% of all falls involved fractures and serious injuries (Nyberg and Gustafson 1995). These falls amongst balance impaired elderly patients could contribute to socioeconomic costs for families. This makes it essential for people with balance impairment to undergo rehabilitation to improve their motor skills for postural stability. Physiotherapy often helps in improving the motor skills to these patients but is often accompanied by physical limits and occupational hazard. In a study by Broom et al., stress was found to be a major factor for physiotherapists which affected their personal and professional lives (Broom 1996). Relationship, and improper allocation of time, inadequate staff and reception of incompatible demands were identified as significant role stressors (Deckard and Present 1989). Such exhaustion over a period of time is likely to lead to disinterest among physiotherapists which could then lead to a paucity of such professionals. Moreover, rehabilitation therapies are often time-consuming and require one or more therapists for proper assistance (Lackner, DiZio et al. 1999).

Robotic rehabilitation treatments could relieve personnel burden by making the patient self-reliant during physical therapy, and therefore in turn reducing costs for health care providers.

Assistive robotics has a wide range of application domains. Examples can be found in the area of power augmentation robots, rehabilitation robotics, as well as orthotic devices (Otsuka 2011, O'Neill, Patel et al. 2013). The rapidly expanding human-robot interaction (HRI) field enables facilitation for healthcare professionals and new rehabilitation possibilities for patients and the elderly. Robotic treatments could quantitatively assess the recovery level of, for example, patients’ motor ability through online measurements of movement pat- terns and forces during training (Diaz 2011). However, we believe that haptic guidance plays a key role in clinical routine activities because touch may derive emotional well-being benefits, such as a feeling of trust and safety for the patient (see chapter 5). This also affords postural control adaptations in the patient which are important because balance control relies on relative self-motion information from visual, acoustic, and haptic sensory information (Blumle, Maurer et al. 2006).

Most of the robotic-assisted systems are rigidly linked to patients' bodies and control their movements similar to exoskeletal orthoses. O' Neill and colleagues developed a reconfigurable mechanical device to physically couple a human with a KUKA LWR4 robotic arm to assist him/her during eating (O'Neill, Patel et al. 2013). This mechanism allowed patients to cater to a wide range of human-robotic applications (Otsuka 2011, O'Neill, Patel et al. 2013). Having a mechanical device physically connected to patients' bodies limits the degree of freedom of the affected limbs compared to naturally occurring muscle activation (Hidler and Wall 2005).

For this reason, we argue for a light touch assistive robotic system which reduces the constraints on the human arm. An unconstrained human-robot interaction should also significantly increase the patient's safety during the treatment.

In this respect, light haptic guidance would enhance safety and simultaneously integrate a caregiver therapy technique which is already used in daily caregiver work. Caregiver-patient interactions for postural support require complex interpersonal coordination, for which the haptic modalities are essential. Understanding human-human interaction from the point of view of haptic interactions is essential to improve human-robot interaction.Beneficial effects of tactile feedback on postural control, are already shown, whether it is static (Kouzaki and Masani 2008, Albertsen 2012, Baldan, Alouche et al. 2014) or dynamic, in the way of unstable surfaces or due to interpersonal touch conditions (Wasling 2005, Johannsen, Guzman-Garcia et al. 2009). What is missing in the literature to date is the effect of robotic dynamic light touch on humans' abilities of postural control. Hence, study III tries to investigate the effect of robotic light touch on humans' abilities of postural control. The ROLITOS group (see summary page 3) aimed to gain further insight into human robot applications for balance rehabilitation in this interdisciplinary study.

11.2 Outlook of study III

This study was conducted to investigate whether tactile feedback given by a robot in KUKA I (spring loaded bracelet (300N/m) and in KUKA II (end effector without any mechanical coupling) can be equated as beneficial balance control to tactile feedback provided by a human being during MFR (see figure 11).

To this end, we designed a functional reach task and compared human-human balance performance with human-robot balance performance.

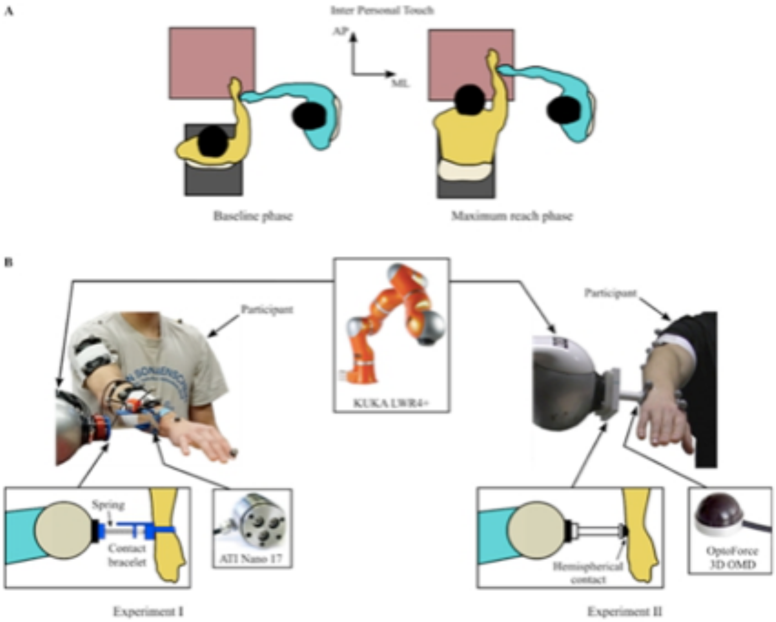

Figure 11 . Experimental setup. (A) Execution of the maximum forward reach task with human interpersonal touch (IPT) support. (B) Robotic IPT conditions for experiment KUKA I (left) and experiment KUKA II (right).

In general, MFR was similar in touch and no touch conditions. This may depend on a combination of several factors, such as the comfort level of the participant with haptic guidance from the robot and the human, and a previous study by Steinl & Johannsen also shows no significant difference in MFR, reinforcing the result obtained with our testing conditions (Steinl and Johannsen 2017).

In general, beneficial effects on reducing body sway were found in RT as well as in IPT. This will be explained in more detail in the general discussion of this dissertation (see chapter 12).

Overall, study III suggests that the guiding effect of IPT and RT can behave similarly, indicating that a robotic device may replace a human therapist without compromising the effectiveness of the rehabilitation treatment.

12 General discussion

This dissertation was dedicated to the study of interpersonal light touch interactions for balance support. Due to the lack of efficient manual handling guidelines the interpersonal light touch strategy was presented in this work. It is supposed to be a promising way to augment control of body balance. On the one hand it allows fairly independent balance rehabilitation on the patient side and on the other hand it could be used to reduce the load on the caregiver.

With respect to fall prevention the study of interpersonal patient-therapist interactions is much needed. The increasing number of falls and the resulting consequences of reduced quality of life, injuries and even death demand for further fall prevention research.

The experiments on sensory feedback availability during dynamic interpersonal coordination (study I) and on the level of participant engagement of the patient during balance exercises (study II) should improve the scientific knowledge on interpersonal interactions in general, specifically on patient- caregiver interactions for balance support.

This work tried to enhance the state of the art on the potential stabilizing effects of light haptic cues during interpersonal interaction for balance support.

Finding answers to this objective is furthermore of critical when thinking of prospective use in the field of assistive robotic equipment for balance rehabilitation (study III). With regard to this challenging approach, the experiments were able to demonstrate that the guiding effect of IPT and RT behave similarly, indicating that a robotic device may replace a human therapist without compromising the effectiveness of the rehabilitation treatment.

In conclusion the findings of our three studies were able to tackle the aims of this dissertation. In particular, improve the understanding of interpersonal interactions as well as clinician -patient interactions and lastly transfer the human-to-human intercation into a robotic solution.

In addition the results of our experiments (study I, II and III) give valuable input for manual handling guidelines. Based on the reported encouraging findings, the question which is left open is what the perspectives from these results will be for interpersonal balance coordination and rehabilitation. In the following these perspectives will be demonstrated and discussed. The author will try to point out how this work enlarged the state of the art. Further, the author will discuss how the interpersonal light touch strategy could contribute to tackle the concerning demand for efficient practical manual handling guidelines.

Perspectives study I

Initially this work aspires to enhance the insight of interpersonal interactions using light touch in general (study aim I).

Study I (see chapter 9) intended to compare the influence of various sensory feedback modalities (vision / touch) in the provision of interpersonal light touch for postural control in maximum forward reaching in healthy individuals. We hypothesized that additional haptic feedback would increase reaching distance and stabilize control of body balance in the contact receiver. We expected the spontaneous interpersonal coordination would be altered by the sensory information available for both partners.

The results from study I can be found in the results section of paper I (page 46).

Partners in a joint action need to coordinate their tasks relying on shared information, while facing different amount of task knowledge and action roles. In order to understand IPC during the provision of IPT on the grounds of ecological principles of interpersonal affordances (Travieso and Jacobs 2009), we believed a joint action in an asymmetric interpersonal context, is an adequate tool to investigate leader-follower relationships (Richardson, Marsh et al. 2007, Vesper and Richardson 2014).

Changing the relative difficulty of two complementary tasks in a joint action context is one way to manipulate the leader-follower relationship. Creating an asymmetry in task-relevant knowledge is another. Vesper and colleagues demonstrated that leaders knowing the target locations would support followers not provided with this information in a task which required partners to synchronizing taps to different targets (Vesper and Richardson 2014).

The effect of haptic information and its interplay with the other just mentioned sensorimotor inputs for balance rehabilitation was in the focus of interest of our work.

Study I was successful in demonstrating how interpersonal coordination is affected by IPT and also is altered by the visuotactile context and the OBT presence. In an asymmetrical joint stance posture (see publication I, chaper 9), the less stable per- son's sway benefits strongly from IPT (Johannsen, Wing et al. 2012). An asymmetrical situation is quite often common given when caregivers support patients. Thus, "deliberately light interpersonal touch" could be a reasonable strategy to facilitate a patient's sensorimotor control of body sway (Johannsen, McKenzie et al. 2014).

According to our present results, we like to add that one might also need to consider the context-dependent interpersonal adaptability of a patient. Thus, when a therapist haptically guides a patient, he or she should to ascertain that two preconditions are available: Firstly that the contact receiver does not have access to another tactile source plus secondly that the contact provider prevents him- or herself from adopting a reactive mode of IPC. If these conditions apply, it seems more likely that a patient will become more responsive to the caregiver's haptic guidance.

With regards to practical manual handling guidelines the result's of study I and specifically these two prerequisites enhance the state of the art.

We believe our findings add meaningful knowledge to the ACC guidelines. The instruction that a therapist should guide and reassure a patient is a decent start, we suppose our message which encourages that the contact receiver (patient) should not have a competing tactile signal source adds a more practical and detail direction. Same is supposed to be valid for the reference that the contact provider (therapist) should prevent him- or herself from adopting a reactive mode of IPC.

Further testing in realistic patient-caregiver settings could lead to even more valuable insights in order to improve manual handling guidelines for the future.

Perspectives study II

Building on the first study in a next step we aimed to improve the understanding of caregiver-patient interaction during light interpersonal haptic support (study aim II). This study (see chapter 10) intended to compare the influence of different ways of subject participation in the provision of interpersonal light touch balance support by a contact provider to balance-challenged elderly individuals. In the "traditional", passive IPT mode the participant faced away from the therapist while receiving haptic support to the back and presumably was not able to contribute significantly to the interaction in terms of controlling contact force precision. In contrast, shared grip between the thera- pist and the participant on a handle while facing each other allowed the participant to directly influence the precision of the interaction force by the utilization of the extended arm's full movement degrees of freedom. Generalizing from our previous work on the effects of IPT, we hypothesized that a mode of passive IPT reception would result in more stable body sway with greater stabilization under progressively more challenging sensory conditions.

In addition to changes in body sway, we were interested in characterizing spontaneous interpersonal postural coordination as expressed by the interaction forces and correlations between both individual's spatiotemporal sway dynamics. Inter- estingly, our expectations were not confirmed by the active IPT mode leading to lesser sway variability compared to the passive mode.

The results from study II (see chapter 10) can be found on page (55).

However testing in the lab might be a limitation of study II and may not represent a real life situation. Direct interpersonal contact was not possible due to the use of the handle in order to measure interpersonal forces. We strengthen that especially the identification of the manner in which decision making of a PT and balance performance of a participant interacts is important in addressing balance problems and falls.

Study II explained the outcome of passive and active participation for postural control in a therapeutic context. Our study showed that both support modes are able to improve postural control in a participant.

With respective to clinical manual handling guidelines we assume the results of study II add valuable information for applied balance rehabilitation. This study shows first indications that patient-caregiver interactions during balance exercises might be more effective when interactionists stand face to face. Generally we believe more partnership based methods should be considered due to a better learning context of the participant and an improved therapeutic exposure for future balance rehabilitation research. To specify, if a patient would be able to be participating longer in a difficult postural task in which the patient can work on compensation and restoration strategies this could enhance the therapeutic exposure.

Furthermore partnership based methods could be valuable in order to create a manual handling method which decreases load imposed on the caregiver during the provision of balance support. The patient is more involved in a partnership based interaction than in a non partnership one, were the clinician is likely to be defined to lead the interaction. Thus, partnership based interactions could help to minimize the load imposed on the caregiver.

Perspectives study III

Building on the first two studies, in a final step this dissertation aimed to translate interpersonal interactions for postural control into a robotic device (study aim III).

Study III (see chapter 11) tried to evaluate the outcome of light interpersonal touch (IPT) provided by a human or a robotic system on the control of body balance and posture in healthy young adult contact receivers (CR) during maximum forward reaching (MFR). In two experiments, changes in spontaneous MFR performance were investigated as a function of the mechanical coupling between CR and the robotic contact provider.

In terms of the “cost” of body sway in the MFR end-state in the context of an achieved MFR amplitude, robot IPT was at least as efficient as human IPT. Correlations between parameters of reaching performance and body sway in the MFR end-state were relatively low but expressed a qualitative difference between the two experiments in terms of the influence of the kind of mechanical coupling utilized for the provision of robotic IPT.

A mechanical coupling by a wrist bracelet as in experiment KUKA I increased the association strength between a parameter such as path length on body sway in the MFR end-state. At the same time, it reduced the strength of the coupling between wrist acceleration and horizontal ground reaction force (GRF) in the AP direction. In contrast in experiment KUKA II, mechanically uncoupled robotic IPT did not affect the association between path length and MFR end-state body sway or the strength of the coupling between wrist acceleration and horizontal GRF. Nevertheless, both experiments had in common that the temporal postural coordination between wirst acceleration and GRF showed the shortest delay when it involved robotic IPT in a simpler follower mode. The results of our study showed that CRs altered their MFR behavior in response to the mode by which IPT was provided.

Similar to the discussion of the interpersonal postural coordination in study I (Steinl and Johannsen 2017) we brought forward the argument that CR’s performance could be a result of social facilitation with IPT (Zajonc and Burnstein 1965). Three factors affect the quality of interpersonal coordination: adaption, attention and anticipation (Keller, Novembre et al. 2014) Keller and colleagues argue that anticipatory mechanisms enable an individual to plan their own movements with respect to the predicted spatiotemporal trajectory of their partner’s movements (Keller, Novembre et al. 2014).

According to Sebanz and colleagues successful joint-action involves shared representations, mutual action prediction and the integration of the predicted effects of both individuals' actions (Sebanz, Bekkering et al. 2006).

We speculated, therefore, that minimization of the interaction forces and their variability at the contact location during IPT acted as an implicit constraint and as a task goal shared between both partners (Sebanz, Knoblich et al. 2003), which triggered predictive sway control in each individual and consequently led to in-phase IPC with an average zero lag (Johannsen, Wing et al. 2012) without any consistent leader-follower relationships (Reynolds and Osler 2014). Passive exposure to the prerecorded sway dynamics of another individual via a force feedback device did not result in sway reductions as seen during IPT with an actual human partner, which shows that IPC with IPT reflects a mutually interpersonal adaptive process based on responsiveness in both partners (Johannsen, Wing et al. 2012). Difficulty of the currently performed task and the ability to adapt to the partner determines which individual takes the respective leader or follower role in a joint action context, with the less adaptive individual becoming the leader (Skewes, Skewes et al. 2015).

In terms of the discussion of the maximum forward reach performance we observed general reductions in reaching distance with all forms of IPT, even human IPT. This contrasts with our observations in study I (Steinl and Johannsen 2017). In study I human interpersonal light touch left reaching amplitude unaffected. An altered experimental context in terms of the features of the lab environment, the additional testing conditions or the individual person of the respective human IPT provider could be possible explanations for this general situational effect in study III. Regarding the contrast of human and robot IPT within the context of our current study, however, IPT provided by a robotic system was not found to be disruptive in a negative way. The most general change in behaviour was a reduction in MFR velocity during all conditions with IPT, especially when IPT was provided by a robot compared to both no IPT or human IPT. Despite impressive advances in the recent decade, current robotics engineering is still far way from developing robotic systems enabled to assist human individuals socially, especially during postural activities and balance exercises. The integration of social robotics into clinical practice contains several open issues. Balance-impaired patients are a more vulnerable population requiring much more care than the healthy young adults in study II.

It remains unclear, therefore, if a relatively simple robotic system such as the one in study III delivering light interpersonal touch, would also be suitable and as bene- ficial for individuals with cognitive and sensorimotor deficits cue to neurological disor- der. It seems likely that the responsiveness of actual neurological patients to the context of robotic IPT is much more restricted than in healthy individuals and clinical severity of a patient's impairments might prevent them from interacting with the robotic system in a natural way. Nevertheless, user safety should always have the highest priority. The development of more adaptive robotic systems for a dynamic hospital environment seems imperative. Integrating safe human-robot interaction approaches in a robotic caregiver, as well as investigating the applicability of machine learning algorithms to better understand patients' state and needs, will be the topics of future balance rehabilitation research.

To sum up, beneficial deliberately light interpersonal touch for balance support is easily provided by a robotic system when it is mechanically not coupled to the human contact receiver, irrespective of the system's capability to predict the position of the contact receiver's hand into the future. While a mechanical coupling by a wrist bracelet seemed to change participants' postural coordination during robotic IPT more noticeably, the effects of uncoupled robotic IPT were comparable to human IPT on most parameters. As the robotic system itself was not designed for any form of "social" cognition or hap- tic communication, our study demonstrates that robotic IPT prompted human contact receivers to change their postural strategy to adapt to the robotic system during maximum forward reaching without any diminishment in their postural performance.

To sum up, the first study investigated the influence of visual and haptic sensory information on interpersonal balance coordination in maximum forward reaching.

The second study examined the dynamic interpersonal coordination during exercises for balance rehabilitation between a clinician and elderly subjects with balance insecurities.

And finally in the third study the engineering aim resided in the adaptation of the principles of interpersonal coordination for light touch balance support into a robotic device.

In summary study findings were successful in improving the understanding of light haptic support for control of body balance, hence achieving the objectives of this dissertation.

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15 Statutory declaration

Eidesstattliche Erklärung

Ich erkläre an Eides statt, dass ich die bei der promotionsführenden Einrichtung Fakultät für Sport- und Gesundheitswissenschaften der TUM zur Promotionsprüfung vorgelegte Arbeit mit dem Titel:

Das Zusammenspiel zwischen Wahrnehmung und Handlung bei interpersonellen haptischen Interaktionen mit sanfter Berührung zur Unterstützung der Gleichgewichtskontrolle

in Fakultät für Sport und Gesundheitswissenschaften, Lehrstuhl für Bewegungswissenschaft Fakultät,

Institut, Lehrstuhl, Klinik, Krankenhaus, Abteilung unter der Anleitung und Betreuung durch:

Prof. Dr. Hermsdörfer ohne sonstige Hilfe erstellt und bei der Abfassung nur die gemäß § 6 Ab. 6 und 7 Satz 2 angebotenen Hilfsmittel benutzt habe.

X Ich habe keine Organisation eingeschaltet, die gegen Entgelt Betreuerinnen und Betreuer für die Anfertigung von Dissertationen sucht, oder die mir obliegenden Pflichten hinsichtlich der Prüfungsleistungen für mich ganz oder teilweise erledigt.

Ich habe die Dissertation in dieser oder ähnlicher Form in keinem anderen Prüfungsverfahren als Prüfungsleistung vorgelegt.

Die vollständige Dissertation wurde in____ veröffentlicht. Die promotionsführende Einrichtung____ hat der Veröffentlichung zugestimmt.

X Ich habe den angestrebten Doktorgrad noch nicht erworben und bin nicht in einem früheren Promotionsverfahren für den angestrebten Doktorgrad endgültig gescheitert.

Ich habe bereits am _________________ bei der Fakultät für ______________________________________ der Hochschule ____ unter Vorlage einer Dissertation mit dem Thema ____ die Zulassung zur Promotion beantragt mit dem Ergebnis____ Die öffentlich zugängliche Promotionsordnung der TUM ist mir bekannt, insbesondere habe ich die Bedeutung von § 28 (Nichtigkeit der Promotion) und § 29 (Entzug des Doktorgrades) zur Kenntnis genommen. Ich bin mir der Konsequenzen einer falschen Eidesstattlichen Erklärung bewusst.

Mit der Aufnahme meiner personenbezogenen Daten in die Alumni-Datei bei der TUM bin ich

X einverstanden, nicht einverstanden.

____

Ort, Datum, Unterschrift