Chapter 7

Synthesis

Humans are challenged constantly while manoeuvring in complex environments. However, our understanding of the art of selecting adequate movements is limited, as we lack theories that can describe how adequate movements are selected. In this thesis, we studied whether and how the perceived ability and strategy selection is in accordance with one’s physical ability. Hereby, we introduced a theoretical framework that could explain how adequate movements are selected.

7.1 Summary

The theoretical framework of this thesis was introduced in chapter 1. This framework can help understand how the interplay between perceived ability and actual ability has an effect on the probability of successful movement execution. The adequacy of a movement depends on the integration and quality of the perception of one’s physical ability and of the task requirements. The main objective of this thesis was to understand how adequate movements are selected by assessing the interplay between the perceived ability and actual ability. We focussed on older adults, as discrepancies between the perceived ability and the actual physical ability have been observed for a substantial set in an older population (Delbaere et al., 2010a; Sakurai et al., 2013) and the consequences of selecting an inadequate movement due to such misalignment can be more harmful.

In a first study to understand the underlying mechanisms of producing adequate movement behaviour in older adults, a method to measure the degree of misjudgment was proposed in chapter 2. In this chapter, the association between the perceived and actual gait ability was quantified directly using a virtual walking path. We instructed the participant to walk on a treadmill, while we evaluated the perceived and actual gait ability using a step-width and a walking-speed paradigm.
In the step-width paradigm, we instructed participants to rate their gait ability by indicating the smallest path-width for which they believed they could walk, without stepping outside the path’s boundaries. In the walking-speed paradigm, participants were instructed to walk at the highest speed they believed they could still walk, without stepping outside the path’s boundaries. We computed the path width and walking speed for which 90% of all steps would be placed within the path’s boundaries. The validity of both paradigms was tested. Results showed that a path-width paradigm can validly quantify the degree of misjudgment. In this path-width paradigm, the participants were instructed to estimate the smallest path width they believed they could walk on, without stepping outside the borders of the path. This was compared with their actual ability, which was determined by assessing the stepping accuracy. Evaluation of the degree of misjudgment within this paradigm revealed that the association between the perceived and actual ability was weak (Spearman’s $\rho = 0.31$), which suggested that older adults experienced difficulties judging their gait ability. Although the path-width paradigm can validly determine the degree of misjudgment, the assessment relies on heavy instrumentation and is time-consuming. Therefore, we introduced other stepping tasks that might be used to assess the degree of misjudgment in the next chapter.

Our next objective was to understand whether misjudgment transferred to other daily-life tasks. If one has an inaccurate perception of his/her physical abilities this should be apparent in a range of movements, and as such, the misjudgment should transfer across tasks. Hence, chapter 3 describes the consistency of the degree of misjudgment across different stepping tasks in 9 young and 15 older adults. Moreover, a set of criteria was proposed that can be used to evaluate the validity of a misjudgment task/measure. The results of this experiment showed that the degree of misjudgment was not very consistent across different stepping tasks ($\text{max. } r = 0.42$), even though the perceived and actual ability measures correlated strongly ($r > 0.67$) in all valid stepping tasks. This suggested that our sample could accurately judge their abilities, but it can be questioned whether this also results in adequate movement selection. In chapters 2 and 3, a direct link between the perceived and actual ability was assumed, and the behavioural choice was neglected in these paradigms. The following chapters focus on the behavioural choice, which supposedly emerges from the perceived ability and the perceived task requirements.

In chapter 4, we studied the behavioural choice in 21 older adults and its alignment to their actual ability. To this end, we used a stepping-down task in which the stepping down behaviour was quantified by means of the critical
switching height between optional heel and toe landing strategies. This critical height resembled one’s behavioural choice, which was determined during expected stepping down and assumed to reflect one’s perceived ability. Participant’s actual ability was determined during unexpected stepping down, in which they stepped down earlier than expected. The reactive behaviour that was provoked by this unexpected stepping down (quantified as the ability to absorb kinetic energy), reflected the actual ability. The results of this experiment suggested that older adults do not select their movement strategy on the basis of their actual ability. This conclusion was deducted from the result that the critical switching height did not associate with kinetic-energy absorption during unexpected stepping down (Spearman’s $\rho = 0.03$).

The aim of chapter 5 was to investigate whether context affects adequate movement selection and how potential task consequences alter the behavioural choice. This was studied in 24 older adults by observing how a postural threat changed stepping-down behaviour. The postural threat was induced by a height manipulation, which showed to be an effective manipulator to induce changes in physiological arousal. A more conservative stepping-down behaviour was selected as a consequence of the postural threat (i.e., the critical height decreased under threat). This result is of importance as it indicates that the strategy selection is a controlled variable, that is deliberately adjusted to fit the perceived needs of the environment. Furthermore, in the same chapter, we examined whether older adults who showed an increased fear at elevation would be less adaptive than their peers that did not show an increased fear response. The participants were split into fear groups, and their stepping-down behaviour in high- and low-threat conditions was compared. Results suggested that the between-group differences in how participant adjusted their stepping-down behaviour to our postural threat, were negligible, probably due to the relatively low induced fear levels.

In the final study, described in chapter 6, we investigated whether a behavioural misjudgment is predictive of the probability of success in daily life. Our theoretical framework dictates that a poor judgment of one’s actual ability could lead to inadequate movement selection, and therefore a lower probability of success. As such, falls in older adults seems to be a product of inadequate selected movements. Hence, we investigated in 55 older adults whether a misjudgement term could improve fall prediction models. We registered falls in a ten months follow-up and compared the predictive power of the behavioural model over conventional models either with or without the addition of misjudgment. Three experimental models were compared to a default model containing the conventional measures: FESi (Yardley et al., 2005) and QuickScreen (Tiedemann et al., 2010). In the first
experimental model, we extended the default model with a misjudgment term, that is the interaction between FESi and QuickScreen. The second and third models consisted of behavioural measures, which were determined by the participant’s stepping-down strategy selection (i.e., $h_{\text{crit}}$) and the actual stepping ability (i.e., $x_{\text{act}}$) on two different stepping tasks. Again, the latter model was extended with an interaction term, between $h_{\text{crit}}$ and $x_{\text{act}}$, that represented the behavioural misjudgment. Our findings showed that the experimental models containing information about the misjudgment did not outperform any model without this information. Moreover, none of the investigated models could accurately predict prospective falls ($\text{ROC}_{\text{auc}} \leq 0.64$). This indicated that a misjudgment term that consisted of neither behavioural measures nor conventional measures improved the prediction of prospective falls.

7.2 General discussion

In the previous sections, I summarised the main results and conclusions of the individual chapters. Each of these studies contributed to our understanding of how adequate movements are selected, but also resulted in subsequent questions and points of discussion when combining them in the framework as presented in chapter 1 (Figure 1.1). Hence, in the following sections, I will discuss our finding within the context of this framework on how to select adequate movements. I will highlight gaps that may be left, critically evaluate the conflicting results within and between our experimental chapters and provide scientific and clinical implications of the work presented in the thesis.

7.2.1 Perceiving the task requirements

When a novel motor task is encountered, humans rely mainly on the available visual information to estimate the task requirements for selecting a movement strategy. In relation to ageing, adequate perception of the task requirement is of primary importance to select adequate movements, as reduced visual function (Klein et al., 2003), and loss of visual field (Freeman et al., 2007) are associated with falls.

In this thesis, we left the mechanisms of how the perception of the task requirements is formed untouched. In studies on goal-setting and performance research, task complexity is commonly used as an important determinant, which is closely related to the task requirements but entails more mental processing tasks over longer time-scales. Previous research has shown that perceived task complexity might deviate from actual task complexity (Campbell, 1988; Maynard and Hakel,
Moreover, perceived task complexity predicts task performance better than the actual objective task complexity (Gerhardt and Luzadis, 2009). Hence, further investigation is required to understand how task requirements are perceived, and whether the knowledge of task complexity can be applied to our framework’s task requirements and to learn about its effect on the probability of success.

### 7.2.2 Aligning the perceived & actual ability

An important result from this thesis is that most older adults can give an accurate estimation of their actual abilities in multiple stepping tasks (Figure 3.4). This suggests that humans form representations of their physical abilities, which may be used to plan future movements. These representations are convenient (when accurate), as this allows for swift judgments about which movement strategy to select. On the basis of such a representation, we can select the most optimal strategy for a given task.

However, when we focussed on gait tasks, older adults experienced difficulties aligning the perceived and actual gait ability (Figure 2.2a). This difference between chapter 2 and chapter 3 could not be explained by differences in the study populations between chapters, because similar selection criteria were used, and indeed, the population showed similar characteristics (i.e., age, gender, FESi, handgrip strength, fall history, MMSE). A more likely explanation for the difference between chapter 2 and chapter 3 is that the level of complexity differed between gait and stepping tasks. To illustrate this, in the gait task of chapter 2, we instructed the participant to estimate their smallest path width. This entailed that participants should be able to simulate their performance to predict what their smallest path width would be, which can be considered a complex task in itself. In contrast, in the stepping tasks of chapter 3, participants possibly used some reference anthropometric to relate the task to (e.g., relating step height or distance to a physical entity such as leg length), which makes the task somewhat less complex. A similar argument has been used to describe findings in a functional reach task, in which young adults estimated their arm length (i.e., anthropometric measure) more precise than their postural limits (i.e., ability measure) (Robinovitch and Cronin, 1999). As the smallest walkable path width relies on one’s physical ability, it might, therefore, be more complex to estimate than step height or step length. As producing an adequate movement partly depends on the perceived ability, it involves the accurate perception of both aspects: the anthropometric dimensions and the physical ability. Daily-life tasks, such as obstacle avoidance or ascending stairs, may rely more on one aspect than on the other. However, the performance on measures that relate strongly to fall risk, such as gait stabil-
ity (van Schooten et al., 2015) or postural sway (Zhou et al., 2017), are typically dictated by one’s physical ability, and not by the individual’s anthropometrics. Therefore, for the assessment of the probability of success, we would recommend incorporating a measure of the participant’s actual ability on a gait ability tasks similar to the task assessed in chapter 2.

7.2.3 From a perceived ability to a movement choice

After integrating the perceived ability and the perceived task requirements, a movement choice should be selected according to these perceptions. If the movement choice comes forth from these perceptions, then the perceived ability measure should (partially) correlate to the movement choice. As we studied the movement choice in this thesis by recordings of the strategy selection during a stepping-down task (chapters 4-6), these choices were expected to be (to some degree) associated with the individual’s perceived ability.

This association could be inspected using the dataset from chapter 6, as this dataset was part of a larger cohort study on self-perception in older adults (Weijer et al., 2019). This allowed us to compare how measures of one’s perceived ability, assessed in different tasks, associated with one’s movement choice (i.e., critical height ($h_{crit}$) in the stepping down task). Figure 7.1 shows the resulting association, and indicates that the perceived ability measures do not associate well with the strategy selection in a stepping-down task.

Why does the perceived ability not associate with the strategy selection during a stepping-down task? One simple and apparent argument could be that safety during stepping-down is not achieved by switching to a toe landing. However, our results in chapter 5 indicate that the critical height of switching from heel to toe landings is a function of postural threat, suggesting that safety can be acquired through the differentiation of movement strategies. A more likely argument is that other facets vary between subjects and across tasks. For instance, chapter 4-5 examined the strategy selection in a stepping-down task. The strategy selection might be co-determined by the perceived comfort, as recent studies suggested that young subjects adjusted their movement pattern to gain more comfort (i.e., smaller impact forces), even though these adjustments demanded higher metabolic costs (Zelik and Kuo, 2012; Skinner et al., 2015).

7.2.4 Updates from past behaviour

The probability of successfully executing a movement task is to a large extent determined by the knowledge we have available before task execution (Körding and
7.2. GENERAL DISCUSSION

The quality of the *a priori* information relies on the adequacy of internal (i.e., perceived ability) and external (i.e., task requirement) models. These models are updated and improved after each repetition (Narain et al., 2014), resulting in higher judgment accuracy (Franchak et al., 2010).

Improvements of the accuracy may only occur when the *online* perception of the probability of success is adequate, which is not always evident. A recent study on the perceived postural sway during a balance task in young adults showed that this performance perception was modulated by a postural threat (Cleworth and Carpenter, 2016), implying a context-dependency of the perceived performance. It is still unclear how the perceived performance affects the perceived ability and therefore future behaviour. On the one hand, imprecise updates could make anxious older individuals more likely to select inadequate movements, but on the other hand, might be protective as it may push them towards more safe behaviour.

Rhea et al. (2010) investigated how an illusion affects toe clearance over repe-

![Critical height vs. Perceived ability](image)

**Figure 7.1:** Perceived ability measures at multiple tasks versus the critical switching height. None of the perceived ability measures associated with the critical switching height.
titions in obstacle crossing. They showed that, despite the fact that the overestimated perception of the obstacle height remained unchanged, young participants reduced their toe clearance over repetitions. The authors argued that conscious visual perception is not a necessity for motor adaptations in obstacle crossing. However, since there was no interaction between the obstacle and the participant in this experiment, there are no other sources available that inform the participant on the height of the obstacle aside the visual perception. Hence, we believe that it is not the \textit{a priori} visual perception, but rather the \textit{online} visual perception that provided the information that led to the change in toe clearance. Nonetheless, in our studies, the strategy selection might also have been affected by (sub)conscious perception of the success of stepping down in previous trials at the same step height, as we recorded the landing strategy numerous times over a range of step height. Therefore, future research should illuminate whether strategy selection is subjected to trial-to-trial changes. This can be studied by manipulating the participant’s perception while keeping the task requirement constant. We suggest for example an experiment in which the strategy selection is monitored during multiple stepping down trials from an illusory height difference. The illusion creates a disparity between the expected and actual stepping down height difference, which results in suboptimal strategy selection for the actual step height. If this deviation is noticed by the motor system (i.e., less successful), it should adjust the strategy selection in the following trials to adhere to the actual task requirements.

### 7.2.5 Do adequate movement choices lead to safer behaviour?

Following the theoretical framework in chapter 1 (Figure 1.1), the framework prescribes that inadequate movement choice leads to a smaller probability of successfully executing a task (i.e., $P\text{(success)}$). A decreased $P\text{(success)}$ leads to an increased probability that stability is jeopardised, and therefore, increases the occurrence of balance loss or falls. However, the results in chapter 6, showed that the adequacy of the movement selection did not predict fall risk in older adults.

To understand this finding, we need to take one step back and inspect the

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<tr>
<td>Strategy selection</td>
<td>Behavioural choice</td>
<td>$P\text{(success)}$</td>
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Figure 7.2: Scheme of how falls relate to the experimentally measured strategy selection.
7.3. CLINICAL AND SCIENTIFIC IMPLICATIONS

proposed and studied chain (Figure 7.2) that relate strategy selection to falls. The strategy selection during a stepping-down task was studied in an experimental setting, in which we instructed the participant to perform multiple steps down. Thereby, we assumed that this would give an insight into the behavioural choices in daily life (Figure 7.2, arrow I). The behavioural choice is weighted by the actual ability and the true task requirement (see framework Figure 1.1) and determines the probability of success (Figure 7.2, arrow II). This probability of success is the reciprocal of the chance of erroneous movement. Part of the erroneous movements lead to balance losses that can still be recovered; however, more strenuous errors can lead to falls (Figure 7.2, arrow III).

Yet, we do not know how strong these associations (depicted by the arrows in the scheme) are. For example, our results in chapter 3 demonstrated the task-specific nature of the degree of misjudgment. Likewise, the movement choice may be as task-specific as this degree of misjudgment. As such, experimentally assessed strategy selection might not (entirely) transfer to behavioural choices in daily life (Figure 7.2, arrow I). For the arrows in this chain, the strength of the associations (i.e., arrows) has not yet been established. Hence, to better understand how adequate movements are selected, we should discover the strengths of these associations.

Recently, Weijer et al. (2018) used accelerometer data to extract measurers of actual ability (i.e., gait quality assessed as the sample entropy of the acceleration data) and perceived ability (i.e., perceived gait stability assessed by both FESi, and step length derived from the acceleration data) in 272 older adults. The use of accelerometers allowed them to evaluate the discrepancy between actual and perceived ability in relation to falls in daily life situations. Hence, reflecting on the scheme in Figure 7.2, they achieved to discard the first step (i.e., experimental assessment of the strategy selection) of the chain. Therefore, they excluded the uncertainty related to the association (i.e., arrow I). This was visible in their results as they concluded that the association between falls and gait quality was modified by the older adult’s perceived gait ability. From their result, we infer that the pathways of how the discrepancy between perceived and actual ability lead via movement choice to a probability of success, described in the initial theoretical framework described in chapter 1, might exist.

7.3 Clinical and Scientific implications

The studies described in this thesis aimed to understand the interplay between perceived and actual ability and how this leads to the movement selection in older
CHAPTER 7. SYNTHESIS

adults. We suggested 1) the discrepancies between perceived and actual ability to be larger in an older age group, and 2) the consequences of inadequate motor behaviour to be larger in this age group. In that respect, this thesis on motor behaviour also provides us with some lessons for clinical practices or other research fields.

7.3.1 Clinical implications

In chapter 4, we found that older adults selected strategies that were not dictated by their actual ability. This might be due to an imprecise representation of their actual abilities, as described in chapter 2. Although there is no clinical test available yet that objectively quantify the adequacy of movement selection, we showed in chapter 3 that there are individuals who select behaviour that is not within the boundaries of their actual ability (i.e., the individuals that placed their foot inside the ‘river’ or being overly cautious). Therefore, we suggest that clinicians or therapists should bear in mind that there are older adults that may encounter difficulties selecting adequate behaviour. Especially, when one suspects a patient to 1) overestimate his or her relatively low physical abilities, or 2) being overly cautious with average physical abilities, it might be advisable to evaluate and discuss the intensity, complexity and perceived threat of daily life tasks. However, clinicians and therapists should be aware that a patient’s (mis)judgment is to a large extent task-specific (chapter 3, see also Weijer et al. (2019)) and context-specific (chapter 5).

Besides the potentially devastating physical consequences of a fall in older adults, often falls are accompanied by a substantial increase in the experienced fear of falling. This fear of falling may lead to activity avoidance (Delbaere et al., 2004), and as hypothesised in chapter 5 may lead to inappropriate movement selection. Our results showed that fear induced by a postural threat leads to an adjustment of the strategy selection. It has been argued that the fear induced by such postural threat is related to the fear that older adults experience when they are afraid of falling (Brown et al., 2002). When assessing the patient’s movement and motor ability, clinicians and therapists may incorporate the potential influence of fear, as movement selection is coupled to fear of falling in older adults (chapter 5). Hence, the fear regarding the possibility to fall might hamper the selection of appropriate movement selection and finally lead to a decrease in the probability of success.

In this thesis, we chose to determine the misjudgment on stepping and gait tasks, which are very common within the range of daily activities that our participants perform. Initially, we had chosen these tasks as we believed they would
7.4. CONCLUSION

give a glance into the participant’s overall misjudgment. However, our analysis revealed the task-specificity of the misjudgment. Therefore, we suggest for future studies with the objective to determine the risk of balance loss due to levels of misjudgment to first evaluate the feasibility of examining the perceived and actual ability on a multitude of daily life tasks.

7.3.2 Scientific implications

Movement activities can be regarded as an accumulation of movement actions, and therefore, operate at longer time scales. Although in our experimental studies, we investigated solely the short-term movement behaviour (e.g., stepping down a height difference), the introduced framework may also apply to different time scales. This is extremely evident for example in the ‘route preview’ phase in free climbing. In an extreme sport like this, it is important to judge whether the planned activity – consisting of an ordered combination of task requirements – lies within reach of the actual ability. In the ‘route preview’ phase, the athlete identifies a climbing route and determines how all movement actions should be orchestrated to overcome the requirements of the ascent (Orth et al., 2016). Hence, this hints that our proposed framework might be applicable to the activity time-scale. Again, the same principle is relevant to movement planning in older adults. Movement navigation often entails a combination of multiple smaller motor tasks. Similar to the route previewing in free climbing, movement navigation requires the concatenation of motor planning of ordered tasks. Strolling around the city centre of Amsterdam might be challenging for older adults, as one needs to cross loose bricks, walk on uneven pavement, dodge cyclist, while avoiding approaching non-attentive pedestrians.

7.4 Conclusion

This thesis postulates that moving safely requires the ability to judge whether the biomechanical constraints can be overcome by the motor system. This entails that humans should have a valid and robust perception of their own physical ability. From the series of methods and paradigms that we developed and evaluated to assess the interplay between perceived and actual ability, our collective results showed that the majority of the fit and healthy older adults that we assessed do not align their perceived and actual ability in tasks that may lead to balance loss or even falls (i.e., walking and stepping tasks). From the combination of these tasks it also appeared that the discrepancy between perceived and actual ability is strongly task-dependent, which makes it very difficult to establish a person’s
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misjudgment in one single/general measure. Moreover, a more challenging task makes older adults adapt their perceived ability (i.e., anticipatory behaviour in terms of movement-strategy selection) to match the challenging context. This may have implications for older adults who experience fear in non-challenging situations, as they are likely to adjust their behaviour to their perceived threat. Such behavioural adjustments may, therefore, lead to inadequate motor strategies. Hence, the results address once again the importance of incorporating task context in order to understand how movement behaviour is shaped. While the perceived ability and the resulting movement behaviour may be detached from the actual ability in some individuals, it did not seem to contribute to the increased fall risk in older adults. However, further investigations are needed to fully understand the mechanisms of how the interplay between perceived and actual ability lead to inadequate behaviour, and whether this induces balance loss or even falls over short and longer terms. These findings allow me to conclude that over- or underestimation is not likely to be a human trait, but rather a complex manifestation of multiple psychological facets that may lead to undesired movement behaviour in some daily activities or tasks.