

## REVIEW ARTICLE

# Improving motor performance: Selected aspects of augmented feedback in exercise and health

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### Abstract

Augmented feedback (AF) can play an important role when learning or improving a motor skill. As research dealing with AF is broad and diverse, the purpose of this review is to provide the reader with an overview of the use of AF in exercise, motor learning and injury prevention research with respect to how it can be presented, its informational content and the limitations. The term ‘augmented’ feedback is used because additional information provided by an external source is added to the task-intrinsic feedback that originates from a person’s sensory system. In recent decades, numerous studies from various fields within sport science (exercise science, sports medicine, motor control and learning, psychology etc.) have investigated the potential influence of AF on performance improvements. The first part of the review gives a theoretical background on feedback in general but particularly AF. The second part tries to highlight the differences between feedback that is given as knowledge of result and knowledge of performance. The third part introduces studies which have applied AF in exercise and prevention settings. Finally, the limitations of feedback research and the possible reasons for the diverging findings are discussed. The focus of this review lies mainly on the positive influence of AF on motor performance. Underlying neuronal adaptations and theoretical assumptions from learning theories are addressed briefly.

**Keywords:** *augmented feedback, motor performance, motor learning, motor adaptation, exercise, health*

### Introduction

Learning a new physical activity like juggling is rarely successful at the first try. Most people perform badly at the beginning due to their inexperience. One way to improve the individual performance is trying different strategies to gain gradual success by trial and error learning. Another way is to gather feedback from external sources like a professional instructor or video programmes. In everyday language, feedback is mostly understood as all instructions that derive from external sources. However, the generic term feedback subsumes different aspects. Therefore, feedback must be classified into two subcategories (Schmidt & Lee, 2011): first, (task) intrinsic (or inherent) feedback, which is presented to a subject when performing a motor skill. Intrinsic feedback represents the sensory-perceptual information that is perceived by exteroceptors and interoceptors while

executing a movement. The inalienability of sensory feedback for motor control and motor learning was nicely described by Cole and Sedgwick (1992). The authors illustrated the importance of sensory feedback with the case history of a patient who lost his proprioception after suffering from a purely sensory neuropathy. Despite the fact that only nerve fibres for proprioception were damaged and the efferent motor system appeared normal, the patient was not able to initiate even very basic motor commands at the beginning of his rehabilitation. Only after several years of training was the patient able to master everyday tasks like eating, writing and walking by substituting proprioceptive feedback with visual control. Therefore, intrinsic feedback is commonly considered to be vital for motor control and motor learning.

The second type of performance-related feedback is called augmented feedback (AF). The term

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augmented was chosen as it adds additional information (quantitatively and/or qualitatively) from an external source to the intrinsic feedback. Depending on the situation, AF can be provided in two different ways: either as knowledge of result (KR) or as knowledge of performance (KP). The first consists of information about the outcome of a movement in terms of the environmental goal (feedback about goal achievement). KP instead focuses on the quality or patterning of a movement.

Apart from the beneficial application of AF in exercise studies (e.g. Hopper, Berg, Andersen, & Madan, 2003; Peacock, Westers, Walsh, & Nicholson, 1981), the positive influence of AF is also well accepted in other disciplines such as rehabilitation after stroke (Langhorne, Coupar, & Pollock, 2009), in physiotherapy (Winstein, 1991) or when learning medical skills (Porte, Xeroulis, Reznick, & Dubrowski, 2007). Nevertheless, the way AF actually acts on the central nervous system (CNS) is not completely understood. The scope of this review is to inform the reader about settings in which AF was used in exercise and rehabilitation. Furthermore, limitations when using AF are discussed. Thus, theories of motor learning will only be touched briefly and are part of other publications (Salmoni, Schmidt, & Walter, 1984; Schmidt & Lee, 2011). However, in order to explain some findings in greater detail, information from basic research was included. As the frameworks and the numerous settings and tasks in which AF was used are very diverse, the current review can only focus on a small sample of the research available. The first part of the review describes the modalities of how feedback can be presented, followed by a chapter focussing on exercise studies and health-related research. Finally, the limitations and possible reasons for the diverging results obtained in AF-studies are discussed.

### Feedback modality: KP and KR

As already introduced, AF can either be provided as KP or as KR. For example, KR is given when a coach tells a high jump athlete: 'You cleared the bar by 20 cm' and therefore refers to the outcome or the goal of a movement. KP instead is rather concerned with a movement pattern that the learner has made. It therefore directs towards the movement itself rather than the aim of the movement, for example: 'Your hip was not extended enough when crossing the bar'. Therefore, in most situations KR and KP can be easily distinguished. Feedback about the speed of a tennis serve represents KR, whereas movement descriptions ('Your arm was bent when hitting the ball') reflect KP. However, in situations when the goal of a movement is the movement itself (e.g. gymnastic moves), it is more difficult to

differentiate between KR and KP. Furthermore, AF can be presented while executing the movement (concurrent feedback) and/or after the movement (terminal feedback). In movements with short duration (e.g. tennis serve) it is difficult to incorporate concurrent feedback, whereas in movements with long duration (e.g. visuomotor tracking) subjects can process and use the additional information. During the 1990s, it was suggested that the mechanisms of presenting KR or KP were very much the same despite referring to very different aspects of the performance (Schmidt & Lee, 2011; Schmidt & Young, 1991). What KP and KR have in common is that both sources of information are provided externally. In an experiment where participants had to throw a soft ball as far as possible, Kernodle and Carlton (1992) showed that the group who received KP feedback about their throwing technique displayed better throwing techniques and better throwing distances than the group who received KR about their throwing distance. This was also the case when volleyball players received KP about the most striking error they performed before or while hitting the ball compared to when the players received KR about the balls spatial precision, rotation and flight (Zubiaur, Ona, & Delgado, 1999). More recent research showed that performance after learning with KP or KR will not necessarily be different. However, the learning strategies, which led to these improvements, seem to differ (Hinder, Riek, Tresilian, de Rugy, & Carson, 2010; Hinder, Tresilian, Riek, & Carson, 2008; Kovacs, Boyle, Grutmacher, & Shea, 2010). Hinder et al. (2010, 2008) used visual rotations as a tool to investigate the effects of differences in feedback modality (KP vs. KR) during visuomotor adaptation. In this paradigm, participants had to adapt to a 60° rotation of the visual target. When subjects learned to adapt with the help of KP, they displayed strong after effects in the post trials where subjects were exposed to an environment without visual rotation. In contrast, the participants who only received KR after each trial did not show the same after effects in the post trials (Hinder et al., 2008). The authors suggested that when learning with KP, subjects are able to constantly map the visual information with the motor information and are therefore able to transform visual information into motor commands. However, when learning to compensate for visual rotation with KR, no visuomotor mapping takes place and participants learn an explicit (cognitive) strategy in order to compensate for the imposed rotation.

### AF in exercise

When reviewing the literature, it becomes apparent that numerous ways exist in which AF can be

provided and numerous settings where AF is applied. In this section, we only focus on exercise studies where AF was related to a kinematic and/or kinetic parameter.

### *Kinetic feedback*

Kinetic feedback (forces, torques, etc.) is a widely used source of information for boosting a person's performance during practice and efforts with maximum intensity. More specifically, force feedback was used in many studies to investigate its effects on motor performance and learning. Peacock et al. (1981) were one of the first to show that when subjects performed isometric maximum voluntary contractions of the quadriceps, the presentation of force feedback can lead to increased torque production. In this study, participants randomly received visual feedback about the torque they produced or no feedback at all. When visual feedback was provided, subjects displayed increased torque values compared to when no feedback was given. In a similar study, Hopper et al. (2003) showed that the presentation of force feedback increased the power output during leg press exercises. During cycling, an active pulling during the upstroke phase helps to improve mechanical effectiveness as the active pulling supports the active pushing of the contralateral leg (Mornieux, Stapelfeldt, Gollhofer, & Belli, 2008; Theurel, Crepin, Foissa, & Temprado, 2011). In a series of studies, pedal force feedback was proven to significantly improve cycling effectiveness by increasing active pulling during the upstroke phase (Mornieux, Gollhofer, & Stapelfeldt, 2010; Mornieux, et al., 2008; Theurel, et al., 2011) and during single leg cycling (Hasson, Caldwell, & van Emmerik, 2008). Furthermore, Theurel et al. (2011) reported a greater reduction in maximal power output during prolonged cycling when no feedback was given compared to when pedal force feedback was available.

### *Kinematic feedback*

Kinematic feedback is connected to some movement-related aspects of the learner's performance such as limb position, centre of pressure (COP), centre of mass movements or limb velocity. During running, a recent study by Eriksson, Halvorsen, and Gullstrand (2011) showed that when trained runners received concurrent visual feedback about the vertical centre of mass displacement and step-frequency as a model of mechanical costs, participants were able to modify their running mechanics in a way that reduced their mechanical work against gravity. What remains unknown from this experiment, however, is if subjects were able to run faster or longer with this

modified running technique. Furthermore, it has to be mentioned that a considerable amount of training or prolonged exercise was needed for adaptations in active pulling during cycling (Theurel, et al., 2011) and in reducing the mechanical power during running (Eriksson et al., 2011). Also, during more complex and technical movements, feedback was proven to be beneficial. Wood, Gallagher, Martino, and Ross (1992) demonstrated that augmented visual kinematic feedback can have a positive effect on learning a golf shot. Furthermore, Moran, Murphy, and Marshall (2012) investigated whether high-level junior tennis players could judge whether a tennis serve with maximal effort was faster/slower than the preceding serve. As the subjects were not able to judge their serves accurately, the authors asked two groups to improve their service speed during six weeks of training. One group received AF about the service speed, whereas the control group trained without feedback. The results of this study showed greater enhancements in serve speed in the feedback group in the post as well as for a retention test. The latter study highlights a phenomenon, which may be responsible for the great beneficial role of AF. Without AF, people were not able to adequately rate their (maximal) performance. Thus, it seems that AF might be a powerful tool helping subjects to recognise and evaluate the best trial out of several similar performances. If this is the case, one could speculate that subjects might have learned to repeat successful trials which could explain some of the feedback-related performance gains.

### *Biofeedback*

In individual sports as well as in team sports, the performance of a single person can be the key to achieving maximal success. Therefore, it seems obvious that AF during training and during competition might be an appropriate tool to enhance performance. More specifically, biofeedback has been widely used as it refers to an augmented form of task-intrinsic feedback originating from physical responses like heart rate, blood oxygen level, brain or muscle activity (Magill, 2010). During shooting, goal-directed hand and arm movements are of great importance. In this context, Sitaram et al. (2012) showed that subjects who trained with real-time fMRI learned to increase their blood oxygen level dependent (BOLD) response in the ventral premotor cortex, an area which contributes to the control of head and upper limb movements (especially goal-directed hand movements, visuomotor integration, and visuomotor transformations). These neurophysiological adaptations resulted in a reduction in movement errors. In a more practical approach, Hatfield et al. reported hemispheric asymmetries in

electroencephalography (EEG) recordings in skilled shooters prior to the pulling of the trigger (Hatfield, Landers, & Ray, 1984, 1987). Based on this knowledge, Landers et al. (1991) investigated if consistent changes in left hemisphere activity (measured via EEG) prior to skill execution can be augmented through biofeedback procedures and whether this training would result in better shooting performance in archers. The authors demonstrated that EEG biofeedback can indeed help to improve performance in pre-elite archers. In their study, subjects trained to move a visually displayed bar representing their left or right hemispheric brain activity. The aim was to enhance left hemisphere activity (correct feedback) or right hemisphere activity (incorrect feedback). The participants who received feedback about their left hemisphere activity improved their performance which was not the case in the group that received feedback about their right hemisphere activity. Very recently, a study from Ekblom and Eriksson (2012) demonstrated that biofeedback can also be beneficial in a force production task. They showed that when subjects were instructed to increase the electromyographic (EMG) activity while performing the task, the visual presentation of EMG biofeedback led to increased knee extensor strength compared to when no feedback was provided. However, what remains unknown from these studies is if the changes caused by biofeedback are permanent or have only a temporary effect.

### AF and prevention

In health-related research, a large number of studies were published with respect to the influence of AF on prevention and rehabilitation. One aspect in this area is the prevention of movement-related non-contact injuries in different sports. It is well documented that there is a high risk of lower extremity injury associated with landing from a jump (Arendt, Agel, & Dick, 1999). Furthermore, some studies indicate that there might exist a positive correlative association between increased vertical ground reaction forces (VGRF) and increased lower extremity injury risk (Hreljac, Marshall, & Hume, 2000). Therefore, recently published studies used AF to minimise VGRF when landing from a jump. Different authors reported reduced VGRF when using video-feedback and/or aural feedback (e.g. Onate, Guskiewicz, & Sullivan 2001) possibly resulting in a reduced incidence rate of lower extremity injuries. This finding might be relevant, for example, in the prevention of stress fractures as external factors (besides many intrinsic factors such as bone density or body size and composition) like mechanical loading seem to play an important role in increasing stress fracture risk (Bennell, Matheson, Meeuwisse,

& Brukner, 1999). Therefore, it seems rational to develop training regimes for sports with repetitive loading such as long distance running, volleyball or artistic gymnastics to reduce VGRF. A study by Crowell, Milner, Hamill, and Davis (2010) dealt with the question whether real-time visual feedback displaying data from an accelerometer could reduce the loading of lower extremities during treadmill running. The results showed that most runners can reduce the lower extremity loading, which is associated with stress fractures. However, it has to be highlighted that the not all studies test for permanent changes of performance in a retention test. Although Onate et al. (2001) found significantly reduced VGRF in a one-week post-test, it is unclear whether the use of AF about VGRF actually has positive permanent effects.

A second aspect of health-related research (beyond many others) is postural control. Bipedals like humans are required to balance their high centre of mass over a relatively small base of support. This multi-joint coordination is highly complex and involves spinal as well as supraspinal centres of the CNS in the control of an upright stance (for review, see Taube, Gruber, & Gollhofer, 2008). Improvements in postural control are well known in response to classical balance training with therapeutic devices (Taube et al., 2007) and with devices from leisure or fun sports (Keller, Pfusterschmied, Buchecker, Muller, & Taube, 2012; Lauber, Keller, Gollhofer, Muller, & Taube, 2011; Pfusterschmied et al., 2011). Furthermore, several studies have examined the direct influence of AF on stance stability. One recent study by Taube, Leukel, & Gollhofer (2008) assessed the influence of augmented visual feedback on stance stability. The authors reported a reduced COP displacement when subjects aimed with a handheld laser pointer on a stationary target both when standing on a stable and when balancing on an unstable surface.

In the context of postural control, AF is most often supplied as visual feedback. However, another way to provide additional information is attaching tape over certain areas of the body to selectively provide augmented sensory feedback without adding any mechanical constriction and mechanical pressure on subcutaneous structures (Pinsault & Vuillerme, 2010). In recent studies, somatosensory information from the neck was enhanced by increasing cutaneous feedback through the attachment of adhesive tape to the skin over and around the neck (Pinsault & Vuillerme, 2008, 2010). The authors observed a reduction in the destabilising effect of plantar flexor and trunk extensor muscles fatigue when attaching the tape. Therefore, the authors assumed a kind of re-weighting in the processing of sensory information that depends on the reliance of the different

inputs (Pinsault & Vuillerme, 2010). Expressed in other words, the CNS was able to selectively adjust the relative weights of sensory inputs that were altered by using adhesive tape for sensory feedback augmentation. Interestingly, it seems that the CNS can even use AF that is provided to body parts which are not involved in the direct control of a certain motor task. For example, Vuillerme et al. (2008) found improvements in sway parameters in fatigued subjects when feedback about the sole pressure distribution was provided to the tongue via electro-tactile stimulation. However, not only supraliminal (above the threshold where subjects are able to consciously recognise the stimuli), but also sub-liminal stimuli can affect postural control. Stimuli that are sub-liminal or sub-sensory do not reach the awareness of subjects but seem to influence motor behaviour. In two experiments by Priplata et al. (2002; Priplata, Niemi, Harry, Lipsitz, & Collins, 2003), sub-sensory tactile stimuli were applied to the feet. It has to be mentioned, however, that the authors described their treatment as ‘subsensory mechanical noise’ and not as AF with sub-liminal intensity. Thus, the explanation of the authors was different. They referred to a mechanism known as stochastic resonance in order to explain their results. Nevertheless, from our point of view the application of random sub-sensory input can also be seen as AF with sub-threshold intensity. The stimuli were either given with three vibrating elements in each insole (Priplata et al., 2003) or with several hundred small nylon indenters that passed through the supporting ground and touched the sole of each foot (Priplata et al., 2002). Despite the fact that subjects were not able to detect the stimuli, the authors reported improvements in sway parameters in elderly (Priplata et al., 2002, 2003) and to a lesser extent in young subjects (Priplata et al., 2002). Sub-sensory stimuli to the soles of the feet were also shown to be an efficient instrument for reductions in gait variability in elderly subjects (Galica et al., 2009). These observations might have a high functional relevance due to the fact that in adults above the age of 65 years, a reduced proprioception is associated with an increased likelihood of falling (Judge, King, Whipple, Clive, & Wolfson, 1995). Therefore, sub-sensory stimuli to the feet or attaching tape to certain areas of the human body might enable older adults to overcome postural instability caused by age-related sensory loss.

### Limitations

Most studies presented in this review showed positive effects of AF on performance (e.g. postural control, enhanced forces, faster tennis serves, etc.). Nevertheless, it has to be noted that the settings in

which AF was applied were very inhomogeneous and furthermore, the way AF was provided also differed dramatically. For example, literature about the frequency of feedback leaves the reader with a very unclear picture about the ideal amount of AF. Based on the findings from lever-pulling tasks the guidance hypothesis, for example, postulates that AF guides the learner to the correct response, but can at the same time degrade learning when AF is withdrawn as subjects might become dependent on frequent feedback by neglecting the processing of intrinsic feedback on which they have to rely when AF is no longer present (Salmoni, et al., 1984). This finding was supported by numerous motor learning studies and the guidance hypothesis is therefore well accepted in the field of motor learning (Schmidt & Lee, 2011; Winstein & Schmidt, 1990). However, reports also exist which are inconsistent with the guidance hypotheses. For example, an enhanced performance was reported in a delayed transfer test for a group that was provided with AF when subjects requested it compared to a group that had no influence on the feedback schedule (Chiviacowsky & Wulf, 2002). The authors reported that subjects preferred receiving AF after good rather than after poor trials. These findings seem to be in contrast to the guidance view as it postulates that AF is important after poor trials with large errors. In such a case, AF is assumed to potentially guide the learner to a correct movement. However, Chiviacowsky and Wulf reported that subjects tend to prefer AF after good trials. Particularly in situations when subjects are able to ‘differentiate’ between good and poor trials, AF about ‘poor performance’ might, therefore, be irrelevant. In contrast, receiving AF after a good trial could confirm or reassure the subject that the movement was correct and might help fine-tuning the movement. Therefore, this kind of AF can also be beneficial even though it does not focus on the informational role of AF. Another example showing contrary results to the guidance view was raised by Wulf and Shea (2002), who reviewed for studies showing that learning complex motor skills do not necessarily suffer from high feedback frequencies.

Furthermore, it is important to distinguish between permanent and short-term effects: it is well documented that paying attention to a subject tends to increase subjects performance compared to individuals who experience no interest taken in their performance. This so-called Hawthorne effect (Lied & Kazandjian, 1998) does not reflect learning but can lead to direct performance improvements that could reflect motivational and/or social factors. However, this motivational and/or social factor might also affect motor adaptation in long-term training studies. For example, maximising a parameter like the service speed in tennis could also be

influenced by a higher motivation of the subjects meaning that providing AF could motivate subjects to train with a higher intensity which could, especially in the long-term, result in enhanced training adaptations. It is therefore important to note that the knowledge gained from single studies must be seen in their very specific context (e.g. number of degrees of freedom, movement complexity, competence of learners, etc.) and that a single theoretical model cannot explain all existing results. As mentioned earlier, an extensive body of literature exists dealing with other feedback-related issues like temporal locus or self-selection of feedback which were not the focus of this review but may also play an important role. Other recent studies highlighted that neural adaptations differed depending on the kind of feedback provided (e.g. KR vs. KP, Hinder, et al., 2010, 2008) or the frequency of feedback (Smyth, Summers, & Garry, 2010). Therefore, it seems reasonable to assume that the neural (re-)organisation of movements depends on various variables such as frequency, type of feedback and the nature and complexity of the task requirements as well as subject dependent differences. Thus, we want to point out that the hypothesis and findings gained from one specific field cannot be transferred 1:1 to other fields. Therefore, a single theoretical model cannot take all this different variables into account. As mentioned earlier, there exist different theories that have all been supported by numerous studies but they are all focusing on very specific aspects of feedback research. Other theories, like the schema theory (Schmidt, 1975) or a computational approach (Wolpert & Ghahramani, 2000) can also be used to explain the potential positive influence of AF. However, the underlying mechanisms of how AF affects motor performance may vary depending on the kind of AF (KR vs. KP, kinematic vs. kinetic etc.), the relative frequency of provided feedback, or the task itself (for example, learning a new task vs. maximising one parameter of a movement). Therefore, it is important to further clarify the ways how AF affects learning/adaptation. Schmidt & Lee (2011) suggests at least three possible ways that should be further investigated in the future: first, the informational function claims that AF provides an optimal information value, especially in situations when the learner is uncertain about the reliability of intrinsic information. Second, the motivational aspect takes into account that AF may enrich a learning task making it more interesting which keeps a person alert and may therefore encourages the learner to set higher personal goals. Furthermore, increased motivation can also serve as a reward or punishment and therefore calls for repetition of a correct or change of the incorrect movement. The third function is strongly associated with the schema

theory (Schmidt, 1975) and characterises associations between stimuli and movements. In this way AF serves as a guide to achieve a specific movement target. Hence, the learner develops a schema between internal commands and the movement outcomes dependent on AF.

## Conclusion

AF is beneficial in increasing athletes' performance as well as the process of motor learning and should therefore be applied in sports training, prevention and rehabilitation. However, when looking into literature it becomes apparent that the settings and the way AF can be provided varies greatly. This can not only be attributed to the various settings in which AF was presented and the various modalities AF can be provided but also the subject dependent differences. Furthermore, the lack of control groups, small sample sizes and different methods make it difficult for coaches, physiotherapist, teachers etc. to decide the best possible way AF should be used. Furthermore, the internal processes which facilitate performance, learning, prevention and rehabilitation by using AF are poorly understood. Therefore, additional research is necessary to identify the structural and neural changes going on when using AF. Nevertheless, AF is a useful tool and has relevance not only for athletes, but also for elderly people and patients.

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