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# Optimal Training for Movement Acquisition and Transfer: Does "Externally Focused" Visual Biofeedback Promote Implicit Motor Learning?

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***Context:*** Visual biofeedback has been shown to facilitate injury-resistant movement acquisition in adolescent athletes. Visual biofeedback is typically thought to foster implicit learning by stimulating athletes to focus attention externally (on movement outcome). However, biofeedback may also induce explicit learning if the athlete uses the visual information to consciously guide movement execution (via an internal focus).

***Objective:*** To determine the degree to which athletes reported statements indicating implicit or explicit motor learning after engaging in a visual biofeedback intervention.

***Design:*** Prospective cohort study.

***Setting:*** Three-dimensional motion-analysis laboratory.

***Patients or Other Participants:*** Twenty-five adolescent female soccer athletes (age = 15.0 ± 1.5 years, height = 165.7 ± 5.9 cm, mass = 59.4 ± 10.6 kg).

***Interventions:*** Standard 6-week neuromuscular training intervention (three 90-minute sessions/wk), with added visual biofeedback sessions (2 sessions/wk). For the biofeedback training, participants performed squatting and jumping movements while interacting with a visual rectangular stimulus that mapped key parameters associated with injury risk. After the last biofeedback session in each week, participants answered open-ended questions to probe learning strategies.

***Main Outcome Measure(s):*** Responses to the open-ended questions were categorized as *externally focused* (ie, on movement outcome, suggestive of implicit learning), *internally focused* (ie, on movement itself, suggestive of explicit learning), *mixed focus*, or *other*.

***Results:*** A total of 171 open-ended responses were collected. Most of the responses that could be categorized (39.2%) were externally focused (41.8%), followed by mixed (38.8%) and internally focused (19.4%). The frequency of externally focused statements increased from week 1 (18%) to week 6 (50%).

***Conclusions:*** Although most statements were externally focused (suggesting implicit learning), the relatively large proportion of internal- and mixed-focus statements suggested that many athletes also engaged in explicit motor learning, especially in early practice sessions. Therefore, biofeedback may affect motor learning through a mixture of implicit and explicit learning.

***Key Words:*** anterior cruciate ligament, implicit learning, explicit learning

**Key Points**

- Visual biofeedback may enhance motor learning in people at risk of anterior cruciate ligament injury and is typically thought to promote implicit (relatively automatic) rather than explicit (conscious) motor learning.
- We analyzed oral reports of adolescent elite female soccer players in which they described their interactions with real-time biofeedback purposefully designed to promote implicit learning and reduce the anterior cruciate ligament injury risk.
- Participants described adopting a mix of explicit and implicit learning strategies, suggesting that biofeedback did not necessarily exclusively promote implicit learning and that monitoring how people interact with biofeedback is recommended.

The application of advanced technologies to promote motor relearning in sports populations is a topic of increasing interest. One example of such an application is *real-time biofeedback*, in which athletes are presented with visual or auditory feedback for immediate self-modification of a certain aspect of their physiological function (eg, muscle tension, joint angle[1–4]). In sports research and clinical practice, biofeedback often consists of information presented visually with the aim of modifying neuromuscular or biomechanical aspects of movement. Specific to anterior cruciate ligament (ACL) injury, different types of visual biofeedback technologies have been used to enhance the acquisition, retention, and transfer of safer movement patterns (eg, to reduce the frontal-plane knee-abduction angle), often successfully.[2,5–11] Moreover, recent technological developments have allowed for the integration of various visual presentation modes (eg, projector screens, head-mounted displays) with rapid calculation of biomechanical variables (eg, asymmetric ground reaction force, knee-flexion angle), providing biofeedback stimuli that map to participants' movements in near-real time.[12]

Despite subtle differences in methods, the success of visual-biofeedback manipulations used for ACL injury-prevention and rehabilitation purposes has usually been attributed to eliciting implicit rather than explicit motor-learning processes.[7,13,14] *Implicit learning* is generally defined as learning that "progresses with no or minimal increases in task-related verbal knowledge (eg, facts and rules)"[15(p9)] such that learning occurs "automatically" with limited conscious awareness.[16] *Explicit learning*, on the other hand, is a highly cognitive process. Learners typically accrue significant amounts of knowledge that can be used to describe their performance and deliberately test hypotheses to explore optimal movement solutions. Various interventions designed to promote implicit learning are hypothesized to result in more robust motor learning and transfer,[17–20] especially in high–injury-risk situations, such as a cognitively demanding environment with high performance pressure.[21]

Researchers[7,13,14,22] have presumed that using visual biofeedback will facilitate implicit learning, in part because this form of augmented feedback reduces the need for explicit instruction and diverts attention toward the effects of one's movements (ie, an external focus of attention) rather than the movements themselves (ie, an internal focus of attention). However, to our knowledge, few studies have demonstrated that visual biofeedback does, in fact, promote implicit learning. Indeed, when athletes engaged in self-guided "discovery learning" (and no specific measures were taken to constrain their attention or promote exploratory movement), they engaged in explicit learning.[23,24] Similarly, when using biofeedback, athletes may consciously investigate how the stimulus responds to their movements (eg, "If I move my knee to the left, I can make the stimulus smaller"), thereby promoting explicit learning to achieve desired outcomes.

In short, when using biofeedback to foster motor learning, what is relevant is not only the information that is delivered (ie, the accuracy of the information and its relevance to performance) but also how the information is used by the athlete, because this could lead to markedly different learning processes and subsequent biofeedback modifications. If athletes use the biofeedback to consciously adjust their movements and deliberately test hypotheses about how they need to adapt their movements, then they are likely engaging in *explicit learning*. In contrast, *implicit learning* may occur if the biofeedback enables them to adjust their movements through unconscious processes, with minimal reliance on explicit, conscious control of movement.

We aimed to investigate whether a published visual biofeedback intervention that was purposefully designed to induce implicit learning would indeed promote implicit motor-learning processes. Toward this end, we conducted a short explorative secondary data analysis. Specifically, we analyzed written reports that were obtained during a 6-week neuromuscular-training intervention that was augmented with real-time biofeedback purposefully designed to promote implicit learning.[8] Using an established method,[25] we classified the focus of attention (external or internal) of participants' written self-reports after each week of biofeedback training sessions (2 sessions/wk) to explore the extent to which athletes' statements indicated a more implicit or explicit learning process. An external focus promotes movement automaticity and robustly leads to implicit learning.[26,27] As such, if athletes predominantly reported external-focus statements, then we characterized their learning as more implicit, rather than explicit. By contrast, if athletes predominantly reported internal-focus statements, their learning was most likely to have been relatively explicit in nature. We further explored whether participants' self-reported ease in interacting with the visual biofeedback would be associated with the frequency with which they reported statements indicating explicit learning (ie, statements containing internal or mixed focus). That is, we hypothesized that athletes would engage in explicit, hypothesis-testing behavior when discovering how the feedback responded to their movements.

## METHODS

### Population

We conducted a secondary analysis on the data of 25 young, healthy female soccer players (age = 15.0 ± 1.5 years, height = 165.7 ± 5.9 cm, mass = 59.4 ± 10.6 kg). The prior published work[8] provided data only for the 17 participants who completed both biomechanical and brain functional magnetic resonance imaging (MRI) testing sessions (8 participants did not complete the MRI for various reasons [eg, contraindications to MRI]). However, in this present study, we supplied data for the full dataset of participants who completed the 6-week augmented neuromuscular training (aNMT) intervention (N = 25).

### Intervention

All 25 participants completed a 6-week intervention that consisted of standard[28] neuromuscular training (3 × 1.5-hour sessions/wk, 18 sessions in total) supplemented with visual biofeedback during certain exercises (aNMT; approximately 2 biofeedback sessions/wk; 12 total biofeedback sessions during the 18-session standard neuromuscular training). The biofeedback training involved participants completing a prescribed exercise while interacting with a visual biofeedback stimulus displayed in near-real time on a projector screen. The stimulus is currently patented and adapted for use as part of ongoing clinical trials (NCT 02933008; US Patent US20180125395). Biofeedback training was conducted using both unilateral exercises (pistol squat, Romanian deadlift; 3 × 5 repetitions per leg) and bilateral exercises (squat, overhead squat, squat jump, tuck jump; 3 × 10 repetitions).

As seen in Figure 1, the biofeedback was presented as a rectangular shape on a projector screen that responded in near-real time to the biomechanical variables of trunk lean,

Figure 1. Three-dimensional rendering of a female athlete interacting with real-time biofeedback stimulus during the overhead squat exercise. The shape deformed in near-real time commensurate with biomechanical risk factors associated with anterior cruciate ligament injury. Note that this so-called *augmented neuromuscular-training (aNMT)* stimulus (which has also been presented in some of our earlier work[6,7]) was wirelessly transmitted in real time to video eyeglasses worn by participants (similar to the image shown here), whereas the training stimulus used in the present study was displayed on a projector screen.[12,29,30] No brace neuromuscular training consists of functional exercises that aim to enhance the functional movement, coordination, balance, and proprioception. This particular stimulus provides augmented feedback during the neuromuscular exercises performed, hence the name *augmented neuromuscular training*.

knee-to-hip joint-extensor moment force ratio, knee-abduction moment of force, and vertical ground reaction force ratio while participants performed various exercises (eg, double-legged squat). While they exercised, we simply asked them to achieve a "goal shape" (eg, a perfect rectangle), which would correspond to an injury-resistant movement (eg, lesser knee valgus). However, if an individual moved with biomechanics associated with a higher ACL injury risk (eg, greater knee valgus or asymmetric loading, insufficient knee or hip flexion), then the rectangular stimulus would become distorted in a manner commensurate with the severity of the deficit. Participants were instructed to maintain the shape of the rectangle throughout each task but were deliberately not given explicit oral instructions about how to achieve this. Please refer to a previously published work[8] for a more detailed description of the intervention. Note that we did not present any outcome data related to the biomechanical effects of the intervention. Significant longitudinal improvements in biomechanical parameters (eg, peak knee-abduction moment) have been reported elsewhere.[8] Please also see a series of preliminary studies[7,14,29,30] supporting the enhanced acquisition, retention, and transfer of injury-resistant movement when athletes trained with this specific biofeedback system.

## Written Responses

At the end of the last biofeedback session for each week, participants answered 2 open-ended questions in writing. These questions were as follows: (1) "Please share your thoughts about any other aspects of the training, including the stimulus display and the technology used for the training" and (2) "How do you think your movements mapped or corresponded to the movements of the stimulus shape?" They also answered 2 closed-ended Likert-scale questions on perceived responsiveness ("Did the shape feel responsive to your movements?") and difficulty ("How difficult was it to achieve the goal shape?") of the biofeedback.

To categorize the open-ended questions, we used a simplified version of the standardized scoring system described earlier.[25] Specifically, we aimed to establish the degree to which a reply could be classified as *externally focused* (EF; indicating implicit learning), *internally focused* (IF; indicating explicit learning), *mixed-focused* (MF; indicating a mixture of the 2), or *other*. Three raters (E.K., T.E., J.H.) established the specific criteria for scoring (see the Table), and then independently scored all answers. They subsequently met to discuss discrepancies (initial agreement = 80% of responses), after which they reached consensus on the final scoring. We present the results in 2 main ways:

1. The frequency (percentage) of external-focus, internal-focus, and mixed-focus responses, combined across the 2 questions and the 6 weeks for which responses were collected. This provides insight into how participants generally focused their attention when interacting with the biofeedback practice.
2. The frequency of external-focus, internal-focus, and mixed-focus responses for each week of practice. This offers more information as to how attentional focus changed in the course of practice.

Finally, to explore whether participants were more likely to report statements indicating explicit learning when they experienced difficulties using the visual biofeedback, they answered questions on (1) the degree to which the shape was responsive to their movements and (2) how difficult they found achieving the goal shape. A 7-point Likert scale was used (1 = *not responsive at all*/*very difficult*; 4 = *sometimes responsive*/*moderately difficult*; 7 = *responsive all the time*/*not difficult at all*). We calculated the median score and interquartile ranges (IQRs) for these variables. Pearson *r* correlations were computed to determine if the scores on these 2 questions were associated with the overall frequency with which athletes reported statements indicating explicit learning (ie, total number of internal- or mixed-focus statements) rather than implicit learning (total number of external-focus statements). For this analysis we created a new variable, using the following equation:

$$\frac{\text{No. of IF} + \text{MF statements}}{\text{No. of IF} + \text{MF} + \text{EF statements}} \times 100\%,$$

where EF = external focus, IF = internal focus, and MF = mixed focus.

**Table.** **Overview of Scoring Methods to Classify the Focus of Attention of Participants' Responses and the Type of Motor-Learning Process These Indicate**[a]

| Category Assigned to Athlete's Statement | Definition | Example | Code | Interpretation in Terms of Explicit vs Implicit Learning |
|---|---|---|---|---|
| External focus (EF) | Focus on movement outcome | ". . . I found it hard to keep [the shape] inside the rectangle" | EF | Indicates more implicit learning[b] |
| Internal focus (IF) | Focus on movement mechanics | ". . . my hips weren't in line with the rest of my body, or my knees went over my toes" | IF | Indicates more explicit learning |
| Mixed focus (MF) | Mixture of internal and external focus | "I moved slowly and tried to keep the box straight" | MF | Mixture of implicit and explicit learning |
| Other type of statement | No clear focus evident | "I think everything was good and everything worked well" | Other | No clear indication of either motor-learning strategy |

[a] Examples are from the current data set.

[b] By definition, it is very difficult to probe *implicit learning*, which is typically defined as the absence of explicit knowledge. That said, written reports can be used to explore whether individuals predominantly use an internal or external focus of attention during learning. These concepts largely (though not perfectly) map onto implicit vs explicit motor learning. That is, an external focus is known to promote automaticity of learning and is a recognized implicit learning intervention (eg, Van Abswoude et al,[26] Kal et al[27]; these articles also summarize other commonly used implicit learning interventions). In contrast, an internal focus is known to promote conscious control of movement and thereby contributes to explicit learning. Hence, athletes who more often report external- rather than internal-focus statements are more likely to have engaged in implicit learning during the preceding practice session. A similar scoring method has been used to explore the attentional focus of therapists' instructions and feedback in our previous work (Kal et al[25]).

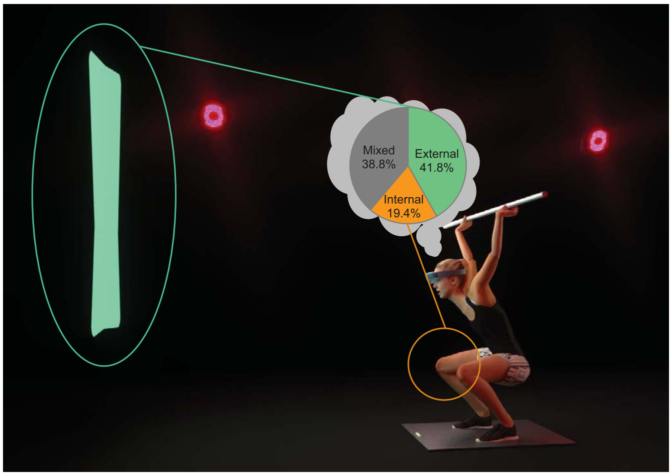

**Figure 2.** **Overall percentage of responses that contained references to attentional focus classified as either *external* (focus on movement outcomes, indicating predominately implicit learning), *internal* (focus on mechanics of movement, indicating predominately explicit learning) or *mixed* (both internal- and external-focus elements within the same response). Note that 60.8% of written responses did not fit any attentional-focus classification (*other* responses) and were not shown here.**

## RESULTS

Five participants did not provide written responses to the 2 open-ended questions in any of the sessions. The remaining 20 individuals provided 171 written responses in total. Of these, 60.8% concerned *other* statements that did not fall into any isolated or combined attentional-focus classification (eg, "It went well"), whereas 39.2% of responses could be assigned to a particular attentional focus. Of the latter, most statements were externally focused (41.8%), closely followed by mixed attentional focus (38.8%), and 19.4% were internally focused (see Figure 2). The changes in attention focus over time are depicted in Figure 3. We observed a relatively gradual increase in external-focus statements from week 1 (18%) to week 6 (50% after the final 2 biofeedback sessions).

All 25 participants completed the closed-ended questions. These questions were both scored on a 1- to 7-point Likert scale, warranting the presentation of median values.

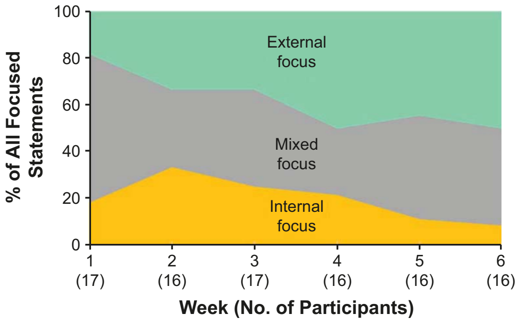

**Figure 3.** **Percentage of external-focus, internal-focus, and mixed-focus statements for each week of training. Responses were collected after the second (and last) biofeedback session for each week. For this graph, we estimated the percentages for each category of statements reported for that session (ie, across participants). Not all participants provided responses for each week of practice. The number of participants for whom responses were available is indicated per week.**

Participants rated the biofeedback as being relatively responsive to their movement (median = 6; IQR = 5–6, range = 5–7) yet moderately difficult to use (median = 4, IQR = 4–5, range = 3–7). We observed no association between perceived responsiveness and the reporting of internal- or mixed-focus statements ($r = .041$, $P = .873$). A moderate, nonsignificant correlation for perceived difficulty ($r = .453$, $P = .059$) suggested that participants who found the feedback easier to use more frequently reported internal- or mixed-focus statements. Of the 20 participants who provided open-ended responses, 2 supplied statements that were classified exclusively as *other*. Accordingly, these were not included in this correlational analysis (total n = 18).

## DISCUSSION

Our analyses indicated that a visual biofeedback stimulus designed to promote implicit learning for the acquisition, retention, and transfer of improvements in biomechanical factors associated with ACL injury induced both implicit and explicit motor-learning strategies in participants. The majority (42.4%) of the athletes' statements were focused externally, which is associated with more implicit, automatic control of movement[31,32]; nonetheless, the relatively high proportion of mixed (36.4%) and, to a lesser extent, isolated internal-focus (21.2%) statements suggested that many participants also engaged in some degree of explicit learning. This especially seems to have been the case in the early learning phase, given that we noted a relatively low frequency of external-focus statements in week 1 (18%), which then increased gradually over the 6-week practice period (up to 50%).

These unexpected findings highlight that when practitioners develop and use biofeedback specifically to promote implicit motor learning, such a strategy by itself may be insufficient to ensure that implicit learning does indeed occur. For the current intervention program, athletes were told to maintain the rectangular shape of the biofeedback stimulus, but they were not given any additional instructions or oral feedback regarding how they should move to achieve this. Even so, when interacting with the biofeedback stimulus, many participants seemed to have gained some explicit, verbalizable knowledge about how they could achieve the desired movement outcome, as evidenced by the written report data. Thus, some individuals seemed to have adopted explicit motor-learning strategies during practice (or at least attempted or related doing so). This so-called hypothesis-testing behavior is a prominent feature of explicit learning.[33] However, we emphasize that such explicit learning should not be considered negative per se, and in fact, it may well be very useful for retaining new motor skills (eg, see Kal et al[21] and Toner and Moran[34]). Indeed, prior published work[7,8,14,29,30] using this specific augmented visual biofeedback system has been effective for the acquisition, retention, and transfer of injury-resistant movement. That said, it is important to acknowledge that (1) the majority of the statements concerned isolated external-focus statements (which are associated with implicit learning) and (2) the motor-learning benefits of the biofeedback intervention may to a large extent still be underpinned by implicit processes. Future researchers could explore if those individuals for whom the biofeedback elicits a more explicit learning process show different learning outcomes than those who largely engage in implicit learning when interacting with the biofeedback.

Our results emphasize that practitioners and investigators cannot simply assume that using visual biofeedback during motor learning will result in implicit learning by default. The stimuli we used in the present biofeedback intervention simultaneously mapped onto multiple biomechanical risk factors. In theory, this multidimensional approach to fuse and transform data on different aspects of movement may limit an athlete's ability to develop an explicit strategy. Even so, athletes often reported statements indicative of explicit learning. We hypothesize that related interventions using real-time visual biofeedback isolated to a single biomechanical variable (eg, knee-abduction angle only) may induce even greater explicit learning, as it would be easier for athletes to discover a strategy for 1 (than multiple) variables.[2] In line with this, our exploratory correlational analysis results, though nonsignificant, might suggest that athletes who found the feedback easier to use more often conveyed statements indicating explicit learning (internal- and mixed-focus statements). It seems that, as these athletes identified how the biofeedback responded to their movements, they began to consciously use this knowledge to guide their movements. This in turn may have given them a greater sense of control and perceived ease of use and possibly made the biofeedback more enjoyable or engaging to interact with during training.

This brief report is not without its limitations. First, the open-ended questions that we based our analyses on were not originally devised to infer modes of learning but rather were intended as an evaluation of the intervention and stimulus design more generally. Nonetheless, we ensured reliability of the analysis via a rigorous process of scoring, consistent with that in an earlier study.[25] Further, due to missing responses and the relatively small sample, we did not have sufficient data for a more in-depth (statistical) analysis of changes in attentional focus over the entire 6-week training period. We did present some basic changes in frequencies, but more detailed and fine-grained (qualitative) data would be needed to further probe such changes. On this point, using written descriptions to examine implicit learning has intrinsic limitations (eg, see Frensch and Rünger[35]). Most importantly, if people move in a fully implicit manner, by definition, they would not be able to characterize their movements at all (which could partially explain the high percentage of *other* statements in this study). Therefore, more in-depth study is needed to explore motor-learning strategies when engaging with biofeedback. Finally, our sample consisted of young, female athletes only, which may limit the generalizability of the results. For instance, relative to young athletes, older athletes may adopt different learning strategies when interacting with biofeedback. Also, younger athletes may also have found it relatively difficult to answer the open- and closed-ended questions in our study, as these had not specifically been validated for this particular population; thus, we cannot be sure if the 12- to 18-year-olds processed the questions as intended, and in some cases, they may simply not have answered because they did not fully understand the questions. We further recognize that changes in self-reported focus over the 6 weeks may have been, in part, due to the progressive changes in exercises while interacting with the visual biofeedback. For example, athletes may engage in more (or less) implicit learning strategies when completing relatively slow bilateral squats versus more ballistic tuck jumps. Future researchers should consider the potential significance of exercise type while using visual biofeedback, including its relative influence on self-reported focus and overall learning strategies.

## PRACTICAL APPLICATIONS

Our findings suggest that practitioners and researchers may need to take additional measures if they aim to elicit implicit learning. First, practitioners and researchers should always monitor what athletes are actually focusing on or attending to when engaging with biofeedback. Although we used a relatively elaborate coding scheme, a simpler way to achieve this would be to ask athletes to complete a self-report tool that assesses the degree to which they consciously process their movements during practice (eg, the state Movement-Specific Reinvestment Scale[36]). Second, if biofeedback was used with the specific aim of promoting implicit learning, and such checks revealed that athletes were highly conscious of their movements during practice (indicating explicit learning), this might signal to practitioners that additional measures are needed to constrain an athlete's focus or interpretation of the biofeedback. Several methods have been described elsewhere that could be used for such a purpose.[27]

In conclusion, our data indicated that real-time biofeedback in a program to reduce the ACL injury risk may promote both implicit and explicit learning. Many athletes may benefit more from implicit than from explicit learning strategies, yet explicit learning may sometimes be more beneficial, depending on individual constraints (eg, working memory capacity or proprioceptive acuity[21]). Future examination is warranted to determine whether constraining an athlete's attention to, or interpretation of, biofeedback modulates the adoption of implicit or explicit learning strategies. Future authors could also establish if tailoring biofeedback (eg, on a continuum from implicit to explicit learning) helps optimize learning outcomes.

## CONFLICT OF INTEREST STATEMENT

Gregory D. Myer has consulted with Commercial entities to support application to the US Food and Drug Administration but has no financial interest in the commercialization of the products. Dr. Myer's institution receives current and ongoing grant funding from National Institutes of Health/NIAMS Grants U01AR067997, R01 AR070474, R01AR055563, R01AR076153, R01 AR077248 and has received industry sponsored research funding related to brain injury prevention and assessment with Q30 Innovations, LLC, and ElMinda, Ltd. Dr. Myer receives author royalties from Human Kinetics and Wolters Kluwer. Dr. Myer is an inventor of biofeedback technologies (2017 Non-Provisional Patent Pending- Augmented and Virtual reality for Sport Performance and Injury Prevention Application filed 11/10/2016 (62/420,119), Software Copyrighted.) designed to enhance rehabilitation and prevent injuries - Drs. Myer, Diekfuss, Bonnette, and Riehm receive licensing royalties related to this copyright. Dr. Diekfuss and Dr. Hogg also receive author royalties from Kendall Hunt Publishing company.

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