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MOVING ON SLOPES: ISSUES AND CHALLENGES FROM A BIOMECHANICAL PERSPECTIVE

Hermann Schwameder

Department of Sport Science and Kinesiology, University of Salzburg, Austria

Moving on slopes is part of daily living locomotion, but also several sport disciplines are performed on inclined terrain. From a biomechanical perspective locomotion on slopes is a challenging task as additional work has to be done compared to locomotion on flat terrain. Moving downwards supports the locomotion due to gravity, however, steep slopes often lead to high speeds caused by the transfer of potential to kinetic energy. Then locomotion is accompanied with the challenge to control speed. Another issue is the aspect of joint loading when moving on slopes. An increase of potential or kinetic energy is associated with an enhancement of work done by the joint structures. The purpose of the presentation is to characterize the specificity and challenges when moving on slopes from a biomechanical perspective including performance, coordination, safety and joint loading in daily movement and sport related tasks.

KEY WORDS: walking, hiking, skiing, ski-jumping, joint loading, inclination

INTRODUCTION: Moving on slopes is a task of daily living locomotion and is primarily conducted as walking or gait. Even in topographically flat regions one is faced with locomotion on sloped walkways or stairways. These types of locomotion are even more frequent and pronounced in mountainous regions due to the specific topographic conditions with inclined roads and pathways. Several sport disciplines are performed on inclined terrain. Beside the Olympic sport disciplines for summer (e.g. cycling, mountain biking, BMX, skateboarding, canoeing) and winter sports (e.g. alpine skiing, ski-jumping, cross country skiing, luge, skeleton) locomotion on slopes emerge in other sports like hiking, mountaineering, climbing or trail running.

While in locomotion on level terrain the net work is zero, concentric, isometric and eccentric work has to be done on the muscle and joint level for moving segments relative to each other as a requirement for successful locomotion. When moving uphill or downhill a net positive or negative work respectively has to be done. So from a pure mechanical perspective locomotion on sloped terrain is a challenging task as additional work has to be done and more energy is needed in general compared to locomotion on flat terrain.

This is true for both daily living and sport locomotion settings. While walking in daily living primarily and pragmatically aims to handle the routine tasks, sport activities in general pursue other purposes as performance enhancement, health issues, competition or purely fun. From a biomechanical perspective moving upwards is associated with primarily concentric muscle activity leading mainly to controlled situations. Moving downwards supports the locomotion due to gravity, however, steep slopes often lead to high speeds caused by the transfer of high potential to kinetic energy. In these cases locomotion is accompanied with the challenges to control speed.

Another issue that should be covered from a biomechanical perspective is the aspect of joint loading in locomotion on slopes. An increase of potential or kinetic energy caused by the inclination is associated with an enhancement of positive or negative work done on the structures of the joints involved in the locomotion. This might cause a substantial increase of joint loading in general and of loading on the diverse biological structures like bones, cartilages, ligaments, tendons and muscles. The potential effect of overloading could lead to pain, impairment and injuries, but also might exceed the threshold for achieving a bio-positive adaptation of these structures.

The purpose of this presentation is to show and to characterize the specificity and challenges of moving on slopes from a biomechanical perspective including aspects of performance, coordination, safety and joint loading in daily movement and sport related tasks.

ALPINE SKIING AND SNOWBOARDING: Alpine skiing is characterized by gliding or carving down snowy slopes of different and changing steepness in a controlled way. In both recreational and elite skiing the specific challenge from a motor control and biomechanical perspective is to anticipate and to react on the permanently changing conditions and movement affecting factors in terms of e.g. terrain, steepness, snow conditions and equipment in an appropriate way for controlling speed, coordination and joint loading.
In several studies aspects of lower extremity joint loading have been addressed based on field studies using 3D kinematics and portable 3D force plates (Kistler) as input data for inverse dynamics calculations (Klous et al, 2010; Stricker et al., 2009). The studies yield both expected, but also not expected results regarding the comparisons of skiing technique (carving vs skidding; Klous et al., 2012), laterality (inside vs outside ski; Klous et al, 2012; Klous et al., 2014) and the disciplines skiing and snowboarding (Klous et al., 2014). Average vertical knee forces for the inside and outside leg of a carved turn are 0.50 and 0.76 times body weight, respectively (Klous et al., 2012). These forces are clearly higher than the average vertical forces working at the inside and outside leg in skidding (0.41 and 0.48, respectively). In anterior-posterior and medial-lateral direction, knee forces in the outside leg are higher for carving, whereas for the inside leg knee forces are larger for skidding (Klous et al., 2012). Regarding the moments, higher average and peak moments are found for skidding, except for the average and peak flexion-extension moments at the inside leg in carving. The comparison of skiing and snowboarding also show deviances regarding the magnitude and the direction of the differences depending on the analyzed loading parameters (Klous et al., 2014).
Biomechanical analyses have also been used to justify the changes of the turning characteristics and the “aggressiveness” of ski equipment (Kröll et al., 2015). The high injury rate in elite race skiing has provoked the FIS (International Skiing Federation) to study the effect of the side-cut radius on skiing technique and joint loading in giant slalom racing from a biomechanical perspective. The results have led to enlarge the side-cut radius from 27 m to 35 m, which has been partly revoked to 30m last season.

SKI-JUMPING: There is hardly any other sport to make use of the acceleration based on moving on a slope for performing a motor task in such an extensive way as ski-jumping. The in-run slope features a decline gradient of about 35° in the first straight part section leading to a take-off speed of up to 30 m/s within 6 s on a ski-flying hill (HS 240). The specific challenges in ski-jumping are to gain a maximal in-run speed, to execute a technically clean and explosive leg extension during take-off, to move into a stable flight position as quick as possible during the early flight phase, to position the body-ski-system during stable flight in a way to maximize the lift-to-drag-ratio for a long flight and to perform a technically clean landing in a telemark position similar to lunges (Schwameder, 2008). From a biomechanical point of view the performance in ski-jumping is substantially determined by utilizing and balancing the forces acting on the system during the different and varying phases and conditions, specifically the phases with and without ground contact. The methodologies in biomechanical studies in ski-jumping cover kinematics (mainly in hill-jumps, but also in dry-land exercises), kinematics (mainly in dry-land imitation jumps, but also in hill jumps), electromyography, wind tunnel experiments and computer simulation for studying mainly the flight phase (Schwameder, 2012) . Recently a portable force-plate has been developed to measure vertical and ant-post forces on the skis, separated on the front and the rear part of the binding (Fritz & Schwameder, subm.). All these approaches support the understanding of the biomechanical background, provide a fundamental insight and build the basis for the development of the athletes, but also for the equipment and the facilities.

SLOPED WALKING: A substantial number of daily living activities have to be executed on non-level or uneven terrain. Many pathways used in daily life are inclined and also staircases have to be considered as an inclined terrain, even though the foot is planted on a flat support area. Locomotion on slopes is a challenging task due to the differing boundary conditions given in these settings. This is associated with adjustments of the joint angles, but also the

muscle activation for gaining the additional work in uphill walking and for decelerating in downhill walking is more intense (Alexander et al., 2017). The adjustments of kinematics, kinetics and muscle activity are even more pronounced in hiking. Furthermore, the adjustments are also affected by the specific footwear used in hiking (Koukoubis et al., 2003).
The positive effects of hiking have been reported by several studies, but this sport can also cause pain and injuries of the musculoskeletal system (Blake & Ferguson, 1993). Most frequently, pain has been reported in the knee joint during downhill walking (Schwameder, 2004). Based on that several research groups have analyzed the effects of sloped walking on the lower extremity joint kinematics and kinetics (Lay et al., 2006; Schwameder et al., 2005). Downhill walking leads to large increases in knee extension moments with increasing inclination, while uphill walking increases hip extensor, knee extensor and ankle plantar flexor moments with increasing inclination (Lay et al., 2006). Joint moments, however, do not account for changes in muscle activation that may occur during sloped walking when compared to level walking and thus may not reflect the real joint loadings (Haight et al., 2014; Lay et al., 2006). Several studies analysed lower limb joint (Steele et al., 2012) and muscle forces (Correa et al., 2010; Valente et al., 2013) using musculoskeletal models during level walking. In contrast, the number of studies investigating joint (Alexander & Schwameder, 2016b; Haight et al., 2014) and muscle forces (Dorn et al., 2015; Haight et al., 2014) during sloped walking is limited. Based on this background several studies have been conducted to analyze the effect of the gradient on lower extremity joint loading on a general, but also on a muscle specific level.
The use of musculoskeletal models estimating lower limb muscle and joint loads during walking yields more detailed and valid information (Haight et al., 2014; Steele et al., 2012). The computed forces may permit a better understanding of the relative musculoskeletal demands and potential risks of musculoskeletal injuries and pathologies (Erdemir et al, 2007). Some data exist on in-vivo measurements of hip (Bergmann et al., 2001) and knee (Trepczynski et al., 2012) joint forces from direct internal structure force measurements by using instrumented endoprostheses. This type of measurement, however, is limited to participants with impaired function. To analyze a non-impaired population, musculoskeletal models are commonly used to calculate joint loadings (Erdemir et al., 2007). While early studies estimated knee joint forces using 2D-analyses (Schwameder et al., 2005; Kuster et al., 1994), recent models can predict 3D muscle and joint forces by employing more complex quasi-static or dynamic optimization techniques (Haight et al., 2014; Sanford et al., 2013; Dorn et al., 2015). These methodologies have been applied to study the lower extremity joint loading in diverse settings while walking on inclined surfaces. Studies have shown the effect of the gradient of inclination on joint loading in young and healthy population (Alexander & Schwameder, 2016a; Alexander & Schwameder, 2016b; Alexander et al. 2017), but also in obese children (Strutzenberger et al., 2011) and amputees (Alexander et al., 2018).

SUMMARY AND APPLICATIONS: Moving on slopes is a daily living task and is performed in many sports. From a biomechanical and motor control perspective this type of locomotion implies specific challenges and joint loading issues. Exemplarily, some of them are addressed and discussed regarding their sport-biomechanical specificity.

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