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Biomechanical Evaluation of Circles with a Suspended Aid

by

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Dedication

To Eriko

For being my best supporter

Abstract

The objective of this thesis was to biomechanically examine the potential usage and limitations of a suspended aid for practicing circles on a pommel horse. The first study examined the influence of a suspended aid on the pommel reaction forces. Twenty gymnasts performed three sets of 10 circles with and without a suspended aid on a pommel horse under which two force plates were set. The results confirmed that the aid could reduce the magnitude of the pommel reaction forces during circles while maintaining the general loading pattern. The second and third studies analysed circles performed by 18 gymnasts with and without the aid from kinematic and kinetic standpoints, respectively. Three-dimensional motion analysis was conducted based on the coordinates of anatomical landmarks, the pommel reaction forces, and the cable tension in the suspended aid. The results demonstrated that circles with the aid actually appeared to be more desirable in terms of the movement amplitude. However, the slowness of circles was inevitably involved with the use of the aid. Also, the net hip joint moments were altered during circles with the aid due to the external force applied from the aid to the leg segments. Finally, the fourth study tested how circles with a suspended aid would vary depending on the gymnast's level of expertise. Based on the scores given by four judges, the gymnasts were classified into the expert and intermediate groups. Additionally, a developing group of eight gymnasts performed three sets of 10 circles with the suspended aid. They could perform circles on a training apparatus, called a mushroom, but not on a pommel horse. This study revealed that the suspended aid could be used in a progressive manner

depending on the gymnast's level of expertise. Taken together, a suspended aid could function as kinematic assistance to let gymnasts experience a desired movement pattern or reduce the pommel reaction forces for a purpose such as control of training volume or rehabilitation. We suggest that practice of circles with a suspended aid should emphasize (1) shorter total duration, (2) larger shoulder rotation, and (3) greater hip joint stability.

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Chapter 1

General Introduction

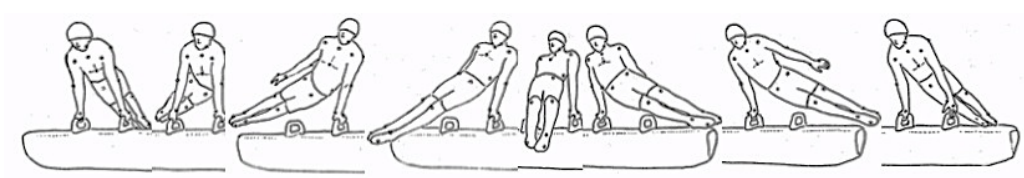
1.1 What are circles?

In 1868, Emil Hafner opened the door to the new paradigm of pommel horse exercises (Karácsony & Čuk, 1998). The key was his innovative skill, "double leg circles." Before then, single-leg pendulum swings dominated the pommel horse routines, which originated in the horse-riding education for knights in the Middle Ages[1-1] (Kaneko, 1974). Knights placed a special emphasis on the elegance of motions demonstrated by pointed toes, straight knees and elbows, and less contact with the horse, forming the fundamental principles of the event. The pommel horse exercises became more popular in the 17th century, and even some technical books were published (Kaneko, 1974). As its popularity increased in Europe, especially in Germany and Switzerland, gymnastics festivals were successfully organized. Then, at one such gymnastics festival in 1868, Emil surprised the spectators by putting his legs together and rotating them over the pommel horse (Kaneko, 1974; Karácsony & Čuk, 1998). This new skill became so popular that it even had influence on the development of the shape of the apparatus (Janssen & Fritsen, 2001). The shorter term "circles" usually refers to

[1-1] Pommel horse is sometimes said to have its origin in the Roman military where soldiers practiced mounting and dismounting a wooden horse (Karácsony & Čuk, 1998; Ichiba, 2005; Janssen & Fritsen, 2001). According to Kaneko (1974), however, these exercises were similar to the modern vaulting exercise in gymnastics. He asserted that the single-leg swings, as seen on the pommel horse, originated in horse-riding education for knights in the Middle Ages.

"double leg circles" rather than "single leg circles," and in the *Code of Points*, the traditional longer term has been replaced by the shorter version (International Gymnastics Federation, 2009).

Circles can be defined as a group of skills in which a gymnast rotates his lower extremities horizontally alternating his upper extremities to support his body. It is composed of four phases: front support, entry, rear support, and exit (Figure 1-1). A gymnast performs circles on two pommels, the leather surface of the horse, or any combination of them, facing either perpendicular or parallel to the long axis of the horse. Depending on the orientation of a gymnast with respect to the horse, circles may be recognized as a distinct skill from others and given a different value. For example, a circle on two handles (Figure 1-1) is an A-difficulty skill, but a circle on a single handle is a B-difficulty skill. Collectively, however, all circles share the same movement pattern regardless of the orientation of a gymnast.



Front support phase --- Entry phase --- Rear support phase --- Exit phase --- Front support phase

Figure 1-1 Circles on a pommel horse

Circles are extremely important skills; today pommel horse routines cannot be composed without them. In the *Code of Point* (International Gymnastics Federation, 2009), 117 recognizable skills are listed for the pommel horse. Only 19 skills are single-leg pendulum swings, and more than 80% of the skills are based on circles or other circular swings. Furthermore, the highest difficulty related to single-leg swings is D; no skill in this skill group is marked as E, F, or G. Therefore, to compete at a high level, circles and other circular swings play a more important role than single-leg swings. Some practitioners presented the possibility of new skills on the pommel horse (Ogawa & Kato, 1998; Watanabe & Kajihara, 2006), but these skills are still based on circles.

Because circles are the heart of modern pommel horse exercises, much coaching literature emphasizes that acquiring high-quality circles is critical (Arkaev & Suchilin, 2004; Brown & Wardell, 1980; Kaneko, 1979; Karácsony & Čuk, 1998; Taylor, Bajin, & Zivic, 1972; Turoff, 1991). Learning poor-quality circles will limit the further development of more advanced skills on this event. Understanding the significant ramifications, a gymnastics coach struggles with finding the most rationale, safe, effective, and productive set of training for a gymnast to master circles. Its practice, however, is not straightforward. Several difficulties and safety issues hinder learning and perfecting circles.

1.2 Difficulties in learning circles

The mechanical complexity of the motion is definitely one of the difficulties in learning circles. Fujihara, Fuchimoto, and Gervais (2009) concluded that two kinds of rotations combine to produce the horizontal rotation of the legs. One is the rotation of the whole body about the supporting hand. The other is the rotation of the body itself about the mass centre. In short, the horizontal rotation of legs during circles is not a simple single-axis rotation. It is mechanically complicated to generate, maintain, and accelerate such a combined rotation. Furthermore, obstacle avoidance is necessary for successful execution of circles; vertical oscillations are involved to avoid collision with the horse (Fujihara & Gervais, 2010). Although many human motions are mechanically complex, circles are far removed from daily human motions and even other gymnastic movement patterns. No human being develops this movement pattern naturally. The complexity of the movement becomes even more evident due to the remoteness from natural human movement patterns.

For learning this complicated move, Karácsony and Čuk (1998) emphasized the importance of coordination. Coordination, in this context, can be regarded as an ability to move multiple segments in a proper manner to complete a task. The high complexity of the nervous system underlies the simplicity of control in a well-coordinated movement (Turvey, 1990). Well-performed circles appear to the observer to be fairly simple. However, it is anything but simple and can only be executed because of the highly developed nervous system. To train the central nervous system effectively, a Hungarian gymnastics school, which has a great history of pommel horse exercises, believes that circles should be learned when a gymnast is as young as possible and that an enormous amount of practice from a young age develops the desired coordination for circles and a solid foundation for more advanced skills (Karácsony & Čuk, 1998).

However, as is often the case with a young gymnast, a learner may not possess the required upper body strength to support his entire body with only his arms. While performing circles on two handles, gymnasts are subject to 1.1 – 1.2

times body weight in the vertical reaction force on each hand during the contact phases (Markolf, Shapiro, Mandelbaum, & Teurlings, 1990; Fujihara & Fuchimoto, 2005). The upper extremities, which have lost a large part of their supporting capability through the evolutionary change, have to endure approximately the same amount of force as legs do during walking. The lack of upper body strength makes it impossible to bear the whole body weight only with one's arms. The importance of physical preparation for learning circles has been well documented by Goverdovdki & Gratsjov (1991a; b). Here is the first practical dilemma: a gymnast should learn circles as soon as possible, but the lack of supporting strength often keeps young gymnasts from learning and mastering circles.

1.3 Safety issues: wrist problems

The pommel horse appears to be the least dangerous event in men's artistic gymnastics due to the lower risk of neck and back injury, but it is the biggest culprit for one of the most common problems: chronic wrist pain. According to Webb and Rettig (2008), the wrists are the second most frequently injured part of the upper extremity in men's gymnastics.

Although wrist pain is widespread throughout all levels of gymnasts, underlying issues seem different from physically immature athletes to mature athletes. Anatomical research has shown that approximately 80% of the load at the wrist joint is applied to the distal radius in a neutral position, in which the relative length of the distal ulna is within ± 1 mm with respect to the radius

(Palmer & Werner, 1984). When the skeletal structure is immature, ulnar variance is typically negative, that is, the ulna is shorter than the radius. Palmer and Werner (1984) simulated this negative ulnar variance situation and reported that the load applied to the distal radius increased up to 96%. This may explain why a young gymnast often injures the distal radius growth plate (DiFiori, Caine, & Malina, 2006). As a result, it is typical for a skeletally immature gymnast to claim wrist pain on the radial side rather than ulnar side (DiFiori et al., 2006).

The ulnar-sided wrist pain is more often related to a skeletally mature gymnast (DiFiori, 2006; Mandelbaum et al., 1989; Webb & Rettig, 2008). According to Gabel (1998), approximately 80% of skeletally mature gymnasts have positive ulnar variance—a longer ulna with respect to the radius. Mandelbaum et al. (1989) theorized that excessive loading on the wrist might relate to radius physeal arrest, developing positive ulnar variance, which results in triangular fibrocartilage complex tears, articular erosions, and the consequent wrist pain syndrome. Even though other diagnoses for the wrist pain such as scaphoid stress fracture, dorsal impingement, and occult dorsal ganglia have also been identified, all of these overuse injuries are related to the excessive repetition of wrist loading (Gabel, 1998).

Mandelbaum et al. (1989) attributed male gymnasts' wrist pain primarily to pommel horse exercises. There is no other event in which a gymnast experiences so many repetitions of high intensity wrist impacts on a non-spring-loaded surface. The impacts and loading forces associated with pommel horse exercises appear to be too much for the anatomical structure of the wrist (Markolf et al., 1990).

Repetitive stress is most likely to be the main contributor to all common overuse injuries (Gabel, 1998). Note that circles are still the most basic skill on the pommel horse. Automatic processing in the central nervous system for circles is a prerequisite for more advanced skills. This raises the second practical dilemma: a gymnast has to repeat circles countless times to master and perfect them, but not surprisingly, this often results in overuse injuries. Because weight-bearing ability is necessary for most gymnastics skills, the negative impact of wrist problems is not limited to pommel horse exercises but affects the various skills of other events. It is common to hear that a wrist problem caused the early retirement of a prospective gymnast.

1.4 Efforts to reduce wrist problems

Gymnasts often use wrist protection. Traditionally, they have used bandages or wraps around their wrists, but more recently, special wrist braces have been developed to reduce or disperse the pressure on the wrists during training. In cadaveric research, Grant-Ford, Sitler, Kozin, Barbe, and Barr (2003) have demonstrated the effects of the wrist brace (Ezy ProBrace made by Gibson, Inc.) on decreasing the pressure at the wrist joint. If this kind of brace did not have a strap on the palm side, it would become more popular. In fact, it has been seen more in women's gymnastics where, unlike in pommel horse exercises, no sensitive control on the hand is required. Also, some coaches have concerns about the over-reliance on the brace, which might hinder the development of the “protective strength” around the joints, even though no scientific evidence has been presented.

The pedagogical equipment, called a “mushroom,” is one of the best innovations as a training apparatus (See Figure 1-2 on the page 10 for a mushroom). Its arched top surface lessens the excessive hyperextension of the wrists compared to the flat surface of the leather of the horse or other training implements (Karácsony & Čuk, 1998). From a pedagogical viewpoint, it also reduces the fear of hitting a horse, grasping or missing a pommel, and falling from the height (Comaneci & Conner, 1996), and therefore, provides a potentially safer progression for a beginner. Because of its safety and pedagogical value, a mushroom is now used all over the world, even in competitions for young gymnasts in some countries. Based on the same concepts, Watanabe and Murayama (2007) created a training apparatus for learning more advanced skill, which can also be used to practice circles.

Both wrist braces and a mushroom have the potential to reduce wrist problems, but they never assist a gymnast in supporting his body weight. That is, a gymnast must perform circles by himself. Although performing a skill alone in a safer environment is an important stage for learning a skill, it is probably not very effective without physical and mental readiness for the skill. As stated above, young gymnasts may not be physically ready for learning circles. What if a gymnast could practice circles with less loading on his upper extremities? In such a condition, he could attempt to improve circles with less risk of overuse injuries. It could also provide a young athlete with a progressive step to develop the necessary coordination for circles despite the lack of physical strength. Although no single training method can be perfect for learning all aspects of a complicated skill, reducing the load on the arms is certainly a potential method for learning circles, and consequently reducing wrist injuries. The question here is how to achieve training in a gravity-less environment.

1.5 Spotting and a suspended aid

Spotting is often used to reduce physical and psychological stress in the learning process of various gymnastics skills. It can be defined as assistance, from a coach or use of a device, for an athlete to complete a task. Spotting can be used to reduce the risk of injury, to allow a gymnast to experience a movement, or to guide a gymnast to proper technique. Manual spotting allows a coach to adjust the amount of assistance depending on the skill level of the learner, providing the gymnast with gradual progression. At the first stage of learning, a gymnast may be totally dependent on spotting. As the gymnast progresses, the coach reduces the amount of spotting. Eventually, the gymnast becomes independent of spotting. Spotting can be a very powerful teaching method that provides both a safe environment and effective learning. It is no exaggeration to say that, without spotting, gymnastics training could be quite limited due to its difficulty and potential danger.

Nevertheless, manual spotting of circles by a coach is not common for learning circles. Boone (1979) suggested that spotting is not needed for pommel horse exercises. He first discussed that skills on the pommel horse were not as dangerous as those on other apparatus such as high bar. This is true in the sense that it may involve less potential risk of serious injury due to the lower height of the apparatus and the nature of the movement patterns. The second point made by Boone (1979) was the difficulty in benefitting from spotting due to the circular nature of the skills. Takizawa (1984) agreed with this point and recommended that circles not be practiced with a spot. Nakamura, Watanabe, and Kato (1998) challenged this view, introducing a method to directly spot circles using two spotters. Their goal was to let a gymnast experience greater speed and amplitude than what he could produce by himself. They seemed successful, yet they also acknowledged the difficulty in spotting circles.

Spotting circles is more often achieved using a suspended aid. Most commonly, a bucket is suspended above the pommel horse or other training apparatus (Figure 1-2). A gymnast puts his feet in the bucket so that his legs are "suspended." Then, the gymnast performs circles with the suspended bucket. Contrary to spotting by a coach, this is a very popular training method in various

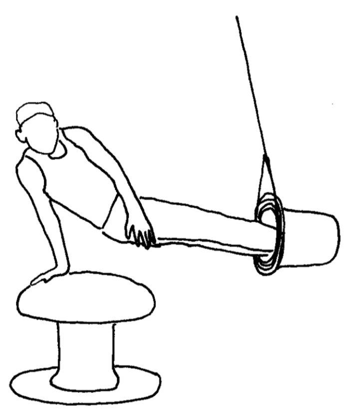


Figure 1-2 Circles with a suspended aid on a mushroom. A gymnast practices circles while his legs are suspended from above the training apparatus.

countries (Comaneci & Conner, 1996; “Development,” 1984; Karácsony & Čuk, 1998; Nakamura et al., 1998; Readhead, 1997; Russell, 1986; Russell & Herb, 1978; Yoshida & Shiroma, 2001).

A suspended aid is often used for young gymnasts as an introductory stage of learning circles. With a suspended aid, even non-gymnasts can experience the motion of circles. Beginners, in particular young children, tend to enjoy doing circles with such an aid, so it is an attractive tool for a coach to motivate children to practice circles. Another possible benefit in using this type of aid is that a gymnast has an opportunity to slow down, to stop, or even to go backward to analyse and understand the movement (Karácsony & Čuk, 1998).

A suspended aid could be used for more advanced gymnasts to polish their technique by allowing them to extend their bodies. Most, if not all, coaching literature underlines that a gymnast should extend his body as straight as possible during circles (Kaneko, 1979; Karácsony & Čuk, 1998; Kenmotsu & Fujimoto, 1978; Takemoto, 1978; Taylor et al., 1972; Brown & Wardell, 1980; Fukushima & Russell, 1980; Yoshida & Shiroma, 2001). To learn high-quality circles, some of these authors believe that the suspended aid should be used not only for introducing circles but also for repetitive refinements of the technique (Karácsony & Čuk, 1998; Yoshida & Shiroma, 2001).

These points would explain its popularity, but there is another possible advantage in using a suspended aid. It most likely reduces the loading on the gymnast’s wrists, although no experimental data was available. That is, more repetition could be made with less potential risk of wrists injuries. Such a training variation may be advantageous to all levels of gymnasts. In his interview, Kashima, the pommel horse world champion in 2003, mentioned that after his shoulder surgery he used a suspended training aid during his recovery (Japanese Gymnastics Association, 2006).

1.6 Aims and scope of this thesis

If a gymnast can practice circles while bearing less load on his upper extremities, such a training method can partly make up a missing progression—direct spotting by a coach—on the pommel horse, providing any level of gymnast with a valuable option for training. As a possible key to this goal, a suspended training aid is often used. Despite its popularity, no scientific data related to the use of the aid were available, and therefore, many aspects of its usage remained anecdotal. This study brought some of these unknowns to light. The objective of this thesis was to investigate the potential usage and limitations of a suspended aid for practicing circles based on the biomechanical evaluation. The following topics were explored.

1) In chapter two, the pommel reaction forces were analysed in detail. The main focus was how the suspended aid influences the magnitude and pattern of loading on the upper extremities during circles.

2) Chapter three answered the question of whether the motion of circles with the suspended aid is different from that of circles without the aid. The main variables were the duration for each

phase, the position of hand contacts and releases, the diameters of horizontal rotations, and the body angles.

3) Chapter four extended the analysis to the field of kinetics. More specifically, the external forces acting on the body were investigated with respect to the motion of the mass centre. Hip joint moment profiles were also investigated to assess the kinetic aspect of the hip motion.

4) Chapter five dealt with the question of whether or not circles with the suspended aid vary among different levels of gymnasts. Using the discriminative variables analysed in the previous chapters, the influence of the expertise of gymnasts on the characteristics of circles was examined.

1.7 Contribution to the fields of biomechanics and gymnastics

To date, the pommel horse is one of the least researched apparatus in gymnastics despite the need for such research. Horizontal circular movements are very different from other representative movement patterns in gymnastics such as somersaults, twisting, and long-hang swing. The amount of scientific research related to pommel horse is very limited, and so is our understanding. Prassas, Kwon, and Sands (2006) appreciated the value of research on pommel horse exercise. The data obtained through this research should be invaluable in the field of sport biomechanics.

In terms of methodology, this study has a couple of highlighted points. First, to examine the hip joint moment profile, two legs are treated not separately but together (Fujihara & Gervais, 2009). Under this assumption, the forces acting between two legs become internal forces and cancel each other out in the system. Modelling the legs as one segment can be applied to many other gymnastic-like skills in which athletes keep their legs together. Even though there is a limitation that any moment on each side of hip joint cannot be determined, this method can still provide useful information about hip motion as a whole.

The second unique element is the method for quantifying body flexion and body lateral flexion separately (Fujihara & Gervais, 2010). Euler's method is currently one of the most common ways to quantify three-dimensional angles. Euler's angles describe the change in orientation as a sequence of three successive rotations. Twelve possible sequences are known (e.g. x-y'-z'', z-x'-y'') (Winter, 2005). It is, however, sequence dependent (Zatsiorsky, 1998). Consider, for example, that one defines a local coordinate system on a thigh segment, and the rotations of the thigh around three axes—x, y, z in the local system—as flexion (or extension), lateral flexion, and axial rotation at the hip joint. In this case, angles would vary depending on which sequence is employed for the computation. The flexion angle calculated with the sequence of x-y'-z'' is different from the flexion angle calculated with the sequence of z-x'-y''. Therefore, the interpretation of the data is difficult. In this study, the projected angle of two segments on a plane defined by the local coordinate systems was used (see the section 3.2 for more details). This may be intuitively more interpretable than

Euler's angle. These two aspects in this study are applicable to other studies in the field.

As previously described, wrist injuries related to pommel horse exercises have been of interest to medical doctors. Without the information about how much force could be reduced by using a suspended aid, it has been difficult for this type of aid to be a possible option for injured gymnasts or those in their recovery process. Circles with spotting may partly fill the gap between two extremes: too much load (regular practice) and no load (no training). Providing reliable information about this training method is beneficial to doctors seeking best practices while treating an injured athlete.

Most importantly, this research contributed to the gymnastics community in very practical ways. A suspended aid is so popular that the training method and importance are described in various regions of the world (Comaneci & Conner, 1996; "Development," 1984; Karácsony & Čuk, 1998; Readhead, 1997; Russell, 1986; Russell & Herb, 1978; Yoshida & Shiroma, 2001). Clarifying the advantages and disadvantages of the method leads to the appropriate use in practice. Through this thesis, the amount of force reduction from the pommels, the kinematic and kinetic characteristics of circles with the aid, and the influence of the gymnast's level were examined. These data are directly related to coaching circles.

1.8 Delimitations

- This study was not intended to investigate motor learning of circles.

It could be a possible extension; however, this study focused on the biomechanical evaluations of circles with a suspended aid.

- This study did not examine any psychological factors that possibly influence gymnasts' performance at the data collection stage. How the experimental atmosphere affects performance was out of the intended scope for this study.
- Because a pommel horse is a men's event, female gymnasts were not included for this study.
- Although a suspended aid can be set in various ways, only one variation was examined.

1.9 Limitations

- Body segments were assumed to be rigid in this study.
- Any translation of joint centres within the body was not taken into account.
- The inherent errors related to body segment parameters were unavoidable.
- By averaging 21 circles, information about individual circles was not presented.
- It was assumed that the twisting belt allows gymnasts to rotate inside the belt with negligible friction.
- Subject availability was limited. Therefore, the statistical power needed to be compromised given this limitation.

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Chapter 2

Circles with a Suspended Aid Part I: Reducing Pommel Reaction Forces

2.1 Introduction

Wrist pain is prevalent in men's artistic gymnastics (Hecht, 2006), and researchers have associated its main cause with pommel horse exercises (e.g. Mandelbaum, Bartolozzi, Davis, Teurlings, & Bragonier, 1989). Common gymnastic wrist injuries, for example distal radius stress injuries, dorsal impingement, and triangular fibrocartilage complex tears, result from repetitive loading (Webb & Rettig, 2008). Even though all six events in men's artistic gymnastics involve upper-extremity weight bearing, the pommel horse is the only one that requires repetitive, high intensity wrist impacts on a non-spring-loaded surface. Therefore, repetitive stress from the pommel horse routines seems most related to wrist overuse injuries (Gabel, 1998).

Although many risk factors are involved with overuse injuries, Hreljac (2004) classified these factors, particularly related to running injuries, into three categories: training, anatomical, and biomechanical factors. If this classification is applied to risk factors in wrist injuries related to pommel horse exercises, training variables would include, for instance, the number of skill repetitions and the duration of practice. Examples of anatomical factors are the hyperextension at a wrist joint, shoulder abduction/adduction angles, elbow valgus, and ulnar variance, which is the relative length of ulna with respect to radius. Biomechanical risk factors can be associated with reaction forces from the pommel horse (pommel reaction forces) similar to ground reaction forces for running injuries. The magnitude of impact (or passive) forces, the magnitude of active forces, and the rate of impact loading are common kinetic variables that are used as an estimate of the loading forces that will transfer through the body (Bartlett, 1999; Nigg, 2000).

Pommel reaction forces were first recorded by Markolf and his co-workers with a load transducer (Markolf, Shapiro, Mandelbaum, & Teurlings, 1990). They reported that the average peak force on each pommel during “circles,” one of the most basic skills on pommel horse (Figure 2-1 top), was approximately 1.1 body weight (BW). They stated that the pommel reaction forces “are remarkably high for an upper extremity joint not normally exposed to weight-bearing loads, and may contribute to the pathogenesis of wrist injuries in gymnastics” (Markolf et al., 1990, p.1001). Fujihara, Fuchimoto, and Gervais (2009) recorded pommel reaction forces on both pommels simultaneously using their pommel horse model with two force plates, reporting that the peak vertical resultant force on both

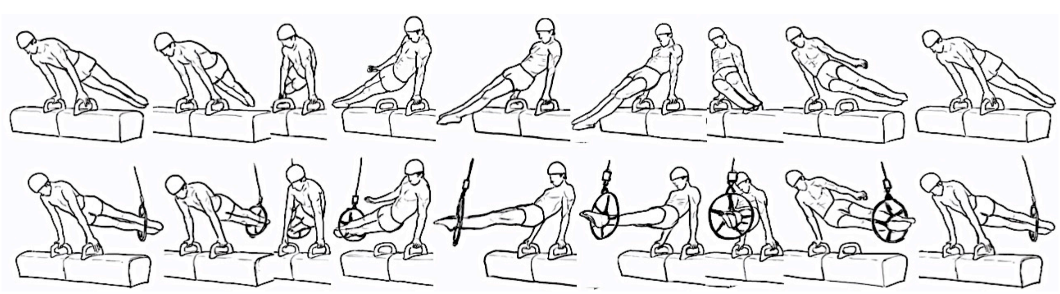

Figure 2-1 Circles (top) and circles performed with the suspended aid (bottom) on a pommel horse.

hands reached approximately 1.8 BW. Typically, elite gymnasts experience hundreds of hand contacts on a non-spring-loaded surface during each training day on pommel horse.

One of the most common training aids, a suspended aid, might provide gymnasts with an opportunity to practice pommel horse exercises with less stress on their wrists. With this type of aid, a gymnast's feet are suspended from above so that his legs are supported (Figure 2-1 bottom). A suspended aid is most commonly used for introducing circles to beginners, but it is also used for more advanced gymnasts to refine their technique (Karácsony & Čuk, 1998). The purpose of this training is usually to replicate spatio-temporal characteristics of circles or better-quality circles. It may also be used to lessen psychological demands, reducing a fear of missing a pommel or allowing a gymnast to concentrate on a certain point in the process of learning. In addition, a suspended aid most likely reduces the pommel reaction force because it does not push down but pulls up on a gymnast. The problem is that, despite its popularity, this training method has never undergone scientific scrutiny. Consequently, its purported training benefits remain as speculative at best.

The aim of this study was to examine the influence of using a suspended aid particularly on the pommel reaction forces during circles. The first question was whether or not the use of a suspended aid reduced the pommel reaction forces during circles. As described above, we hypothesized that force reduction would be achieved with the use of the suspended aid. In addition, this study sought to determine the amount of force reduction and how the force patterns might be affected by using the aid.

2.2 Methods

2.2.1 Participants

Twenty male gymnasts volunteered to take part in the study. They were at least national level, and five of them had international competition experiences. All were capable of performing 20 consecutive circles on two handles of a pommel horse. The mass, height, and ages of the gymnasts were 48.7 ±12.3 kg, 1.55 ± 0.11 m, and 16.7 ± 4.3 years (mean ± standard deviation). They had 9.9 ± 3.5 years of experience in competitive gymnastics and trained 20.3 ± 3.4 hours per week at the time of data collection. All gymnasts had experience in practicing circles with some form of suspended aid but not with the particular aid used in this study. No participant reported any wrist problem that would exclude him from participation in the study. Written informed consent was obtained of all the gymnasts. Prior to the start of this project, ethical approval was obtained through our institutional research ethics review board.

2.2.2 Experimental setup

Two force plates (AMTI, OR6-6-4000), bolted to the laboratory floor, were used to measure the pommel reaction forces. A no-leg pommel horse (Spieth Anderson International Inc.) was cut in half, and each half was fixed to one of the force plates. A 5 mm gap between the two pieces of the horse ensured that forces applied on each half of the horse were measured independently of each other (Figure 2-2).

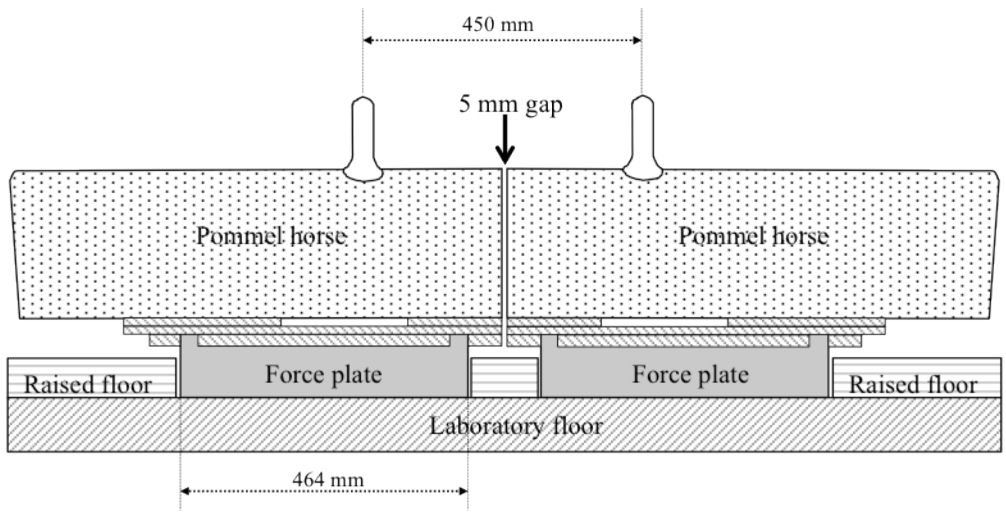

Figure 2-2 Pommel horse setting. A pommel horse was cut into half, and each half was fixed to one of the force plates, which were bolted to the laboratory floor.

A suspended aid was constructed with a rotator twisting belt whose diameter was 0.37 m (Norbert's Athletic Product, Inc.). The inside of the ring frame was arranged so that it fitted to the various sizes of the gymnasts' legs (Figure 2-3). The cable suspending the aid was attached to a swivel on a beam running 4.1 m above the surface of the pommel horse. The height of the aid was set as low as possible while guaranteeing that the aid did not contact the pommel horse during circles. The total mass of the aid was 2.3 kg. The force data were recorded at 1000 Hz.

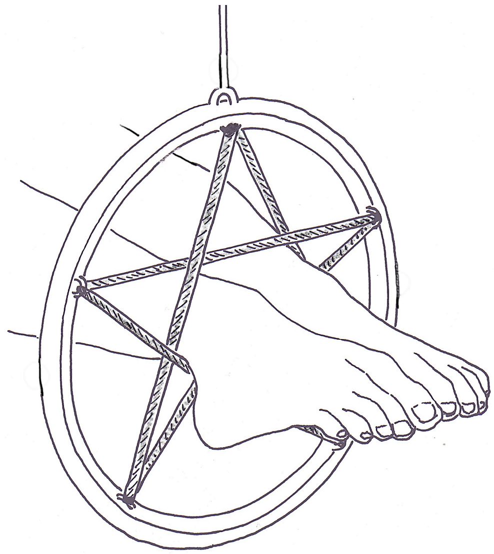

Figure 2-3 The suspended aid developed for this study. It was constructed with a rotator twisting belt whose diameter was 0.37 m (Norbert's Athletic Product, Inc.). A bungee rope was threaded through five hooks making a star. The gymnast placed his ankle joints in the middle space of the star. Then, an elastic wrap was used to assure its location remained fixed on the legs during the trials.

2.2.3 Data collection

After general and event-specific warm-ups, the gymnasts performed three sets of 10 circles on the pommel horse in two conditions: without the aid and with the aid. Either condition was randomly assigned for the first three sets of 10 circles, and then the gymnasts performed another three sets of 10 circles in the other condition. The aid was fixed to a gymnast's ankles using an elastic wrap to assure its location remained fixed on the legs during the trials. To maximize the experimental efficiency, the order of trials was not randomized within a subject. The gymnasts were instructed to practice as much as they needed, but no gymnast practiced more than 30 circles for any condition. No specific instruction about performance was given so that any possible learning effect was minimized.

Between each trial, the gymnasts were given as much rest as they needed to reduce the influence of fatigue.

2.2.4 Data analysis

In this study, all data were considered to be counterclockwise circles to avoid any potential confusion related to the different circle direction. When a gymnast performed clockwise circles, the sign of the medio-lateral component of the force data was inverted. Then, the left hand and the right hand were switched for the following analyses. The force data were smoothed at 100 Hz using a fourth-order Butterworth digital filter and scaled to each gymnast's body weight (BW). Loading time histories, impact and active peak forces, average forces, loading rate, the duration of hand contact and release, and the duration of a single circle were analyzed. Based on Nigg's reference on the characteristics of impact forces, an impact peak was defined as the maximal xyz-resultant peak value that occurred within 50 ms after a contact (Nigg, 2000). An active peak was found as the maximal value during a contact phase excluding the first 50 ms. Loading rate was computed by the regression maximum slope method with three points (Woodard, James, & Messier, 1999).

2.2.5 Statistical analysis

Seven circles out of 10, excluding the first two and the last one, were used so that the mean data for each variable were computed from the data of 21 circles (3 x 7 circles). Note that all discrete values were found for each single circle then averaged. Averaging data was justified by reporting standard error of measurement for each variable as a reliability index (Stratford & Goldsmith, 1997). To examine the influence of using the aid, circles with no aid were compared to circles with the aid. The dominance statistic (Cliff's *d*, Cliff, 1993) was computed as an effect size measure for each comparison. The Wilcoxon signed-rank test was performed for fifteen discrete variables with the Holm's correction, a less conservative measure than Bonferroni which divides the *p*-value by the cumulative number of comparisons (Knudson, 2009). Non-parametric statistics were used in this study due to the small sample size ($n = 20$), as recommended by Kitchen (2009) and Tomkins (2006). The experiment-wise error rate was set at $p < 0.025$, so after the Holm's correction, a critical p value for each test ranged from 0.0017 to 0.0250. All statistical significance tests were performed using PASW Statistics 18.0 (SPSS Inc., 2009).

2.3 Results

2.3.1 Impact peak force and loading rate

The use of the aid reduced both the impact peaks and the loading rates approximately by half (Table 2-1). When the gymnasts performed circles without the aid, the mean impact peak was 0.47 BW on the left hand and 0.82 BW on the right hand. With the aid, these peaks became 0.23 BW and 0.37 BW, respectively. Similarly, the mean loading rate was reduced from 32.6 BW/s to 16.0 BW/s on the left hand and from 24.2 BW/s to 15.2 BW/s on the right hand. The variability was large between the participants and also within a participant. However, the

Cliff's *d* for these variables was at least 0.70, meaning that more than 85% of all values for these variables recorded during circles with the aid were smaller than those without the aid. The impact peak was found approximately 0.02 - 0.03 seconds after a contact, and no practical difference in the time to the peak was found between the two conditions.

Table 2-1 Impact variables between circles with the aid and circles without the aid. The hands are for counter-clockwise circles.

Variables (unit)	Trials	SEM	Range	Mean ± SD	Mean Difference	Cliff's *d*	*z-statistic (p)*
Impact peak (BW)							
Left hand	Aid	0.12	0.08 – 0.44	0.22 ± 0.09	- 0.25	- 0.92	- 3.92 (0.00009)*
	No aid	0.15	0.20 – 0.65	0.47 ± 0.10			
Right hand	Aid	0.19	0.10 – 1.00	0.37 ± 0.22	- 0.45	- 0.75	- 3.88 (0.00010)*
	No aid	0.33	0.37 – 1.35	0.82 ± 0.31			
Loading rate (BW/s)							
Left hand	Aid	11.4	5.9 – 25.6	16.0 ± 6.2	- 16.6	- 0.71	- 3.82 (0.00013)*
	No aid	21.9	15.3 – 55.5	32.6 ± 15.8			
Right hand	Aid	8.5	7.4 – 32.2	15.2 ± 5.7	- 9.0	- 0.70	- 3.50 (0.00046)*
	No aid	12.0	10.5 – 39.8	24.2 ± 7.6			

SEM = standard error of measurement, SD = standard deviation
The stars next to the *p* values indicate the statistical significance. Note that the lowest possible value of *z* statistic for this study was 3.92.

2.3.2 Active-peak forces and average forces

The active-peak forces were significantly attenuated with the aid (Table 2-2). For circles without the aid, the mean active peaks of the xyz-resultant force were 1.13 BW for the left hand, 1.33 BW for the right hand, and 1.96 BW for the both hands. With the aid, these values were reduced to 0.85 BW, 0.86 BW, and 1.20 BW, respectively. The gymnasts generally experienced the larger active-peak forces on the right hand during circles without the aid, but the difference between the hands was decreased with the aid. The aid provided approximately 25% and

35% force reduction for the active-peak values for the left and right hands, respectively.

The significant force reduction can also be seen in the average forces (Table 2-2). The average xyz-resultant forces were reduced to 0.59 BW for each hand from 0.76 BW for the left hand and from 0.78 BW for the right hand. These are equal to 22% and 25% force reduction for the left and right hand, respectively. The average xyz-resultant force for both hands decreased from 1.04 BW to 0.77 BW.

The force reduction was found in all components of the reaction force (Table 2-3). For both the active peaks and the average forces, the greatest force reduction occurred in the backward reaction forces. The smallest differences between the aid and non-aid trials were found in the rightward reaction forces on the right hand and the leftward reaction forces on the left hand, namely, the medio-lateral forces during a single-hand support.

Table 2-2 Active peaks and average of the xyz-resultant forces between circles with the aid and circles without the aid. The hands are for counter-clockwise circles.

Variables (unit)	Trials	SEM	Range	Mean ± SD	Mean Difference	Cliff's *d*	*z-statistic (p)*
Active peak (BW)							
Left hand	Aid No aid	0.04 0.05	0.74 – 1.01 0.98 – 1.32	0.85 ± 0.06 1.13 ± 0.09	- 0.28	- 0.99	- 3.92 (0.00009)*
Right hand	Aid No aid	0.04 0.06	0.75 – 1.01 1.15 – 1.52	0.86 ± 0.08 1.33 ± 0.09	- 0.47	- 1.00	- 3.92 (0.00009)*
Both hands	Aid No aid	0.11 0.13	0.91 – 1.68 1.60 – 2.51	1.20 ± 0.19 1.96 ± 0.23	- 0.45	- 0.99	- 3.92 (0.00009)*
Average force (BW)							
Left hand	Aid No aid	0.02 0.02	0.50 – 0.68 0.67 – 0.85	0.59 ± 0.05 0.76 ± 0.04	- 0.17	- 1.00	- 3.92 (0.00009)*
Right hand	Aid No aid	0.02 0.02	0.51 – 0.68 0.73 – 0.84	0.59 ± 0.05 0.78 ± 0.04	- 0.19	- 1.00	- 3.92 (0.00009)*
Both hands	Aid No aid	0.01 0.01	0.70 – 0.83 1.02 – 1.07	0.77 ± 0.04 1.04 ± 0.01	- 0.27	- 1.00	- 3.92 (0.00009)*

SEM = standard error of measurement, SD = standard deviation
The stars next to the *p* values indicate the statistical significance. Note that the lowest possible value of *z* statistic for this study was 3.92.

Table 2-3 Each component of forces between circles with the aid and circles without the aid. The hands are for counter-clockwise circles.

Variables (unit)		Trials	Mean ± SD				
			Vertical	Forward	Backward	Rightward	Leftward
Active peak (BW)							
	Left hand	Aid	0.82 ± 0.05	0.29 ± 0.06	0.22 ± 0.06	0.17 ± 0.03	0.14 ± 0.04
		No aid	1.06 ± 0.09	0.40 ± 0.04	0.36 ± 0.04	0.25 ± 0.05	0.18 ± 0.04
	Right hand	Aid	0.83 ± 0.07	0.26 ± 0.06	0.25 ± 0.07	0.14 ± 0.04	0.20 ± 0.05
		No aid	1.26 ± 0.08	0.38 ± 0.03	0.45 ± 0.08	0.19 ± 0.05	0.34 ± 0.06
	Both hands	Aid	1.13 ± 0.16	0.37 ± 0.11	0.39 ± 0.13	0.18 ± 0.04	0.17 ± 0.03
		No aid	1.85 ± 0.21	0.60 ± 0.07	0.73 ± 0.13	0.32 ± 0.07	0.24 ± 0.05
Average force (BW)							
	Left hand	Aid	0.56 ± 0.04	0.14 ± 0.04	0.12 ± 0.04	0.08 ± 0.01	0.07 ± 0.02
		No aid	0.71 ± 0.04	0.21 ± 0.03	0.21 ± 0.02	0.12 ± 0.02	0.09 ± 0.02
	Right hand	Aid	0.56 ± 0.04	0.13 ± 0.03	0.12 ± 0.04	0.08 ± 0.02	0.09 ± 0.01
		No aid	0.74 ± 0.04	0.20 ± 0.02	0.21 ± 0.03	0.09 ± 0.03	0.13 ± 0.01
	Both hands	Aid	0.74 ± 0.03	0.18 ± 0.04	0.16 ± 0.04	0.08 ± 0.02	0.07 ± 0.01
		No aid	0.99 ± 0.00	0.28 ± 0.02	0.29 ± 0.03	0.10 ± 0.02	0.09 ± 0.01

2.3.3 Temporal characteristics

Circles were significantly slower with the aid. Circles with the aid needed, on average, 1.69 seconds to complete a single circle, whereas circles without the aid took 0.93 seconds (Table 2-4). The Cliff's *d* was 1.0, meaning no circles with the aid was faster than circles without the aid regardless of the gymnasts. The difference was clear even from visual observation. No instruction for the speed of circles was given to the gymnasts in this study. Therefore, it may be suggested that they performed circles at a self-selected speed of which they felt most confident. As a result, the between-gymnast variability was large for circles with the aid. The range was from 1.38 to 2.30 seconds. However, the ratio of the contact duration to the release duration was approximately 2 to 1 for both conditions.

Table 2-4 Temporal characteristics between circles with the aid and circles without the aid. The hands are for counter-clockwise circles.

Variables (unit)	Trials	SEM	Range	Mean ± SD	Mean Difference	Cliff's *d*	*z-statistic (p)*
Contact duration (s)							
Left hand	Aid No aid	0.08 0.02	0.86 – 1.58 0.60 – 0.71	1.11 ± 0.20 0.64 ± 0.03	0.47	1.00	3.92 (0.00009)*
Right hand	Aid No aid	0.08 0.02	0.89 – 1.65 0.60 – 0.67	1.13 ± 0.21 0.63 ± 0.02	0.50	1.00	3.92 (0.00009)*
Release duration (s)							
Left hand	Aid No aid	0.04 0.02	0.44 – 0.72 0.23 – 0.34	0.58 ± 0.07 0.29 ± 0.03	0.29	1.00	3.92 (0.00009)*
Right hand	Aid No aid	0.04 0.02	0.46 – 0.65 0.25 – 0.36	0.57 ± 0.05 0.30 ± 0.03	0.27	1.00	3.92 (0.00009)*
Total duration (s)	Aid No aid	0.09 0.02	1.38 – 2.30 0.87 – 0.99	1.69 ± 0.26 0.93 ± 0.03	0.76	1.00	3.92 (0.00009)*

SEM = standard error of measurement, SD = standard deviation
The stars next to the *p* values indicate the statistical significance. Note that the lowest possible value of *z* statistic for this study was 3.92.

2.3.4 Loading pattern

When the duration for a single circle was normalized to 100%, the force curves for circles with the aid were similar in shape to those for circles without the aid (Figure 2-4 for each hand and Figure 2-5 for both-hand resultant). The magnitude of the forces was smaller for circles with the aid, but the timing of the peaks and directional changes (e.g. forward – backward or rightward – leftward) were very consistent except for the vertical forces. With the aid, the vertical-force curves were flattened. The clear peaks, seen in circle without the aid, almost disappeared. The vertical forces on each hand synchronized to generate the large peaks of the both-hand resultant forces during the double-hand support phases. Because of the significant force reduction on each hand, the reduction of the peak force was even more dramatic for both-hand resultant force.

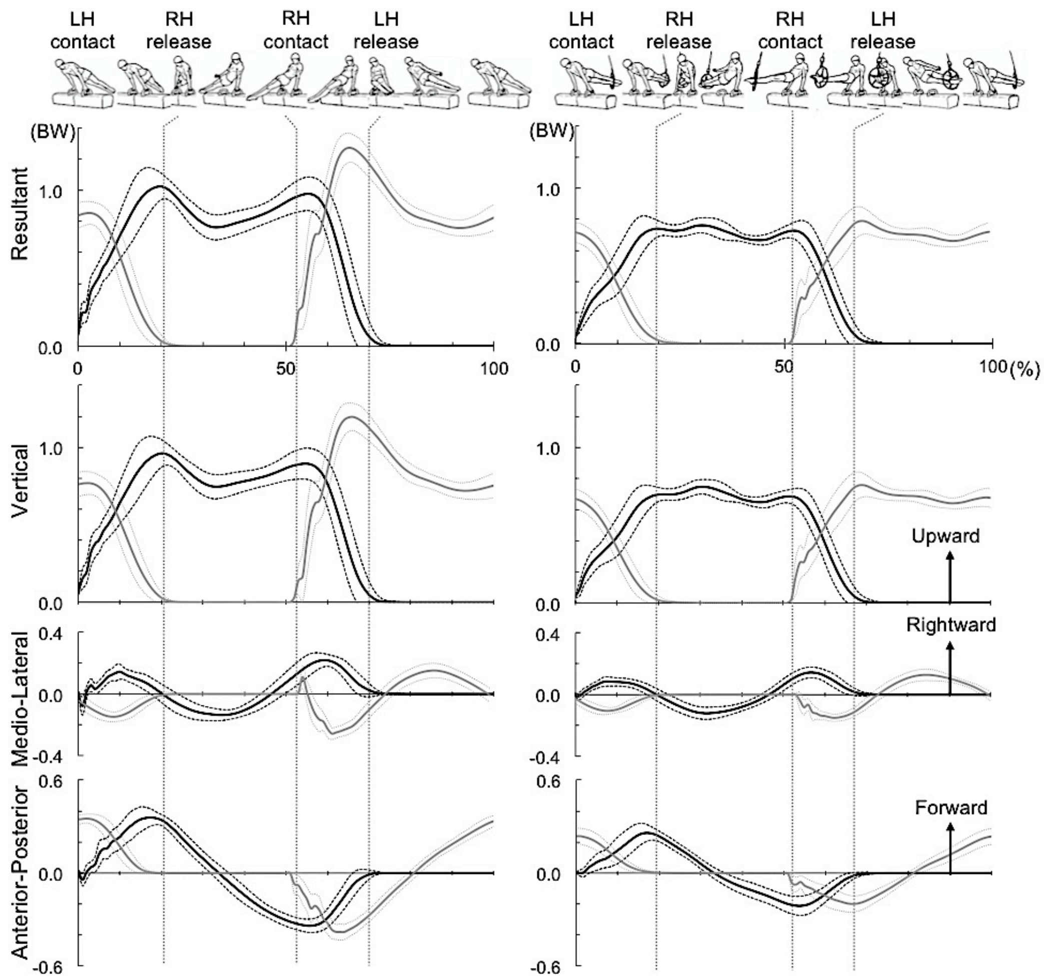

Figure 2-4 The pommel reaction forces on the left (black) and right (grey) hands during circles without the aid (left column) and circles with the aid (right column). The solid lines indicate the average of 20 gymnasts, and the broken lines indicate the ± 1 standard deviation from the average. Twenty-one circles were averaged for each gymnast's data; therefore, the graphs show the average of 420 circles (21 × 20). Note that both impact- and active-peak values were attenuated due to the time normalizing and averaging processes. For the discrete values for these variables, please see the Table 2-1, 2-2 and 2-3. These graphs depict the similar loading patterns during circles with and without the aid, except the vertical component. The force curves of the vertical component were flattened during circles with the aid. It should also be noted that the difference in the temporal characteristics was not reflected in these time-normalized curves.

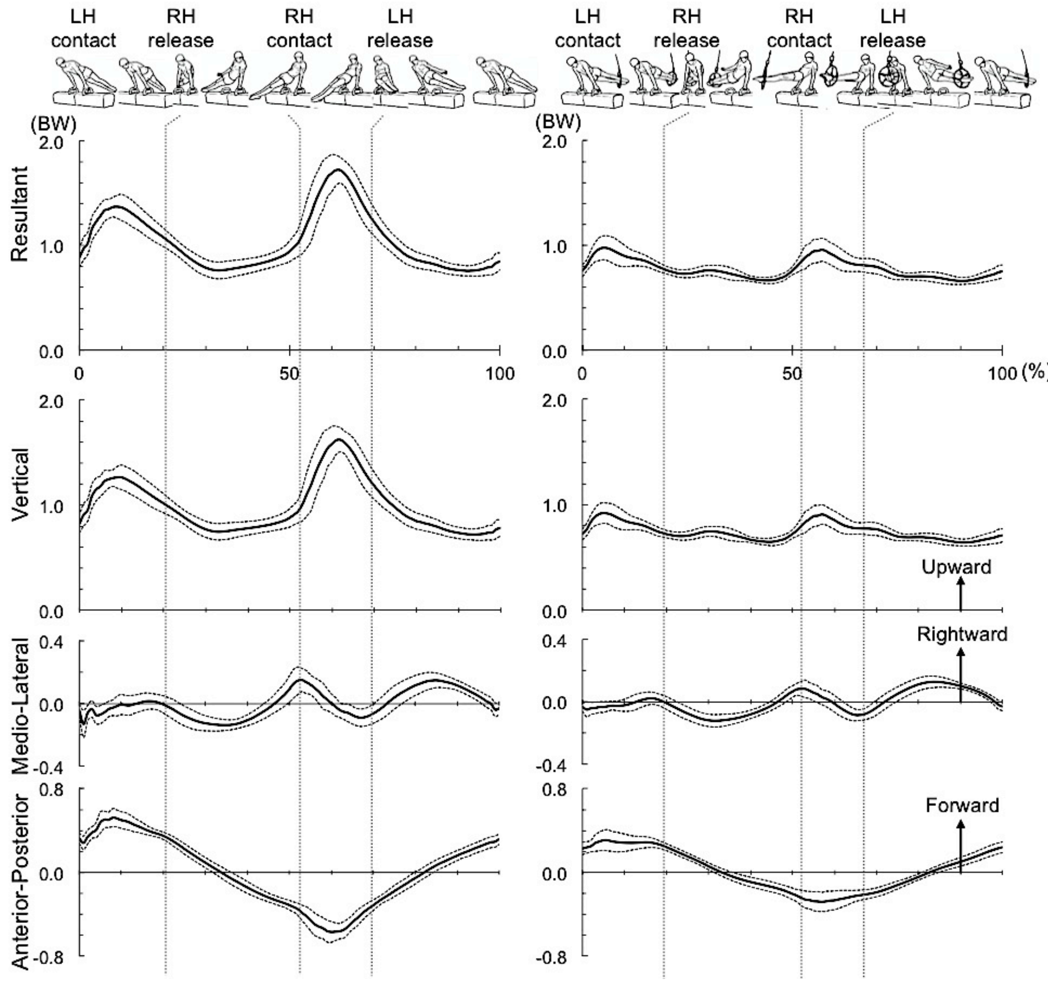

Figure 2-5 The resultant pommel reaction forces on both hands during circles without the aid (left column) and circles with the aid (right column). The solid lines indicate the average of 20 gymnasts, and the broken lines indicate the ± 1 standard deviation from the average. Twenty-one circles were averaged for each gymnast's data; consequently, the graphs represent the average of 420 circles (21 × 20). Note that active-peak values were attenuated due to the time normalizing and averaging processes. For the discrete values for these variables, please see the Table 2-2 and 2-3. These graphs depict the similar loading patterns during circles with and without the aid, except the vertical component. The force curves of the vertical component were flattened during circles with the aid. It should also be noted that the difference in the temporal characteristics was not reflected in these time-normalized curves.

2.4 Discussion

2.4.1 The influence of the aid on the pommel reaction forces

The use of the aid clearly decreased the magnitude of the pommel reaction forces in all aspects, namely, the impact peak, the loading rate, the active peak, and the average forces. These results were expected because of the nature of the aid. It was also possible that the slower motion of circles indirectly contributed to the force reduction. The more important question was how much force reduction could be expected from the use of such an aid. This study showed that the impact peaks and the loading rates decreased to approximately 50% on average. Also, 25 - 35% active-peak attenuation and 22 - 25% average-force reduction resulted from the use of the aid. We found large variability for the impact peak and the loading rate between the gymnasts and even within a gymnast. However, all gymnasts experienced smaller impact peaks with the aid compared to their trials without the aid. The active-peak values and average force can be considered more reliable and valid than the impact-peak values and the loading rates. In no-aid trials, the peak and average pommel reaction forces recorded in this study were similar to the previously reported values (Fujihara et al., 2009; Markolf et al., 1990, Yamada, Takamatsu, Yokozawa, Hasumi, & Koyama, 2008). With the aid, the force reduction occurred in all directions.

Despite the reduction in magnitude, the time-normalized force curves remained similar in shape particularly in the horizontal components. Fujihara et al. (2009) confirmed that the horizontal components of the pommel reaction forces were responsible for the horizontal rotation of the mass centre during circles. This suggests that gymnasts can produce a similar mass-centre rotation on the horizontal plane even with the aid. The aid had a great influence on the vertical loading pattern. Gymnasts generally integrate some up-down motions to avoid collision with the pommel horse (Fujihara & Gervais, 2010). The flattened vertical pommel reaction force implied that the vertical movements of the body were reduced overall. Whether or not this effect is desirable depends on the skill training purpose.

The suspended aid also reduced the asymmetry in loading between the hands. To date, we are unable to locate any literature which studies wrist injuries in relation to the loading asymmetry during pommel horse exercises. However, several studies have reported the differences in the force-loading pattern between the hands (Fujihara & Fuchimoto, 2005; Yamada et al., 2008). The asymmetry in the vertical component seems associated with the up-down motions during circles. As described above, the vertical peak force was attenuated during circles with the aid, so was the asymmetry between the hands. Note that some asymmetry remained even with the aid especially in the horizontal components (Table 2-3). The horizontal components of the pommel reaction forces are responsible for the rotation of circles (Fujihara et al., 2009). Examining such details in technique is beyond the scope of this study, but the similarities in the loading pattern would imply the technical similarities between circles with and without the aid.

2.4.2 The implication and limitation of the study

There are several advantages to having a training option in which gymnasts experience a similar loading pattern on the upper extremities yet with smaller magnitude. A beginner would benefit from such a progressive loading mechanism for developing upper-extremity strength and coordination for learning circles. The specificity is one of the basic training principles (Stone & Stone, 2011). Because the movement and loading patterns of circles are very unique, practicing with a suspended aid can be a precious training option, which may satisfy the specificity principle better than other strength training. We should keep in mind, however, that the rate of force development is also different due to the slower circles with the aid.

According to the idea of the generalized motor program proposed by Schmidt (Schmidt, 1976), one can generalize the overall duration and overall force magnitude of a motion that has been already acquired. Because all participants were able to perform circles even without the aid, it is likely that they could generalize an acquired motor program for circles to perform circles with the aid. A true beginner, who cannot perform circles without the aid, may experience a different pattern of the pommel reaction forces from those reported in this study. However, what is important is that it is possible to have a similar loading pattern during circles even with the aid. In other words, by practicing circles with a suspended aid, a beginner might be able to learn correct weight-bearing patterns that could be eventually generalized to non-aid circles with shorter duration and greater forces. The task similarities would allow us to expect some transfer of learning (Seidler, 2010).

Also, less loading magnitude can help gymnasts practice more with less risk for overuse injuries. Elite gymnasts often train more than 20 hours per week, and several hundreds of circles are expected during daily pommel horse training. Therefore, not only beginners but also advanced gymnasts would benefit from having such a training option to control their training volume as well as to learn more advanced skills beyond circles. The aid can also be useful for gymnasts on recoveries from upper-extremity injury. Takehiro Kashima, the pommel horse world champion in 2003, used a suspended training aid during his recovery from his shoulder surgery (Japanese Gymnastics Association, 2006). The idea is similar to a body-weight-support harness used for walking rehabilitation (e.g. Norman, Pepin, Ladouceur, & Barbeau, 1995).

This study provided novel and valuable information, but a few limitations should be considered. First, one could experience very different impact-peak values and the loading rate from the averaged values reported in this study. These variables can remarkably vary depending on the dynamical situation for a circle, individual re-grasping technique, a definition of an impact peak, experimental setup, and data-processing procedure. Second, the information about actual wrist loading is limited due to measurement limitations such as no detailed kinematic data and the inability to determine the point of force application on the pommel handles. Third, the results were based on only one type of suspended aids. With a different variation of suspended aid, the amount of force reduction might vary.

Finally, no assessment was made from a motor-learning perspective; therefore, whether or not the aid would actually help gymnasts learn circles was not assessed in this study.

2.5 Conclusions

Pommel horse exercises are often associated with chronic wrist pain in men's artistic gymnastics (Mandelbaum et al., 1989; Gabel, 1998). The negative impact of wrist problems is not limited to pommel horse exercises but affects the various skills of other events. This study clearly showed that a suspended aid could reduce the magnitude of the pommel reaction forces during circles while maintaining the general loading pattern. Having such a training variation could be beneficial for all levels of gymnasts. Together with following studies focused on a more technical aspect from kinematic and kinetic viewpoints, the potentials and limitations of a suspended aid, a worldwide-well-known training aid, should be better understood to create a safer and more effective training protocol.

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Chapter 3

Circles with a Suspended Aid Part II: Spatio-temporal Characteristics

3.1 Introduction

"Bucket-circles" is a well-known training method for learning "circles," the most basic skill in pommel horse exercises (Figure 3-1). A gymnast places his legs into a bucket that is suspended from above, and he rotates his legs with the bucket as he performs circles. This type of training aid—a suspended aid—is commonly used as an introductory progression in which gymnasts are first exposed to the overall motion of the skill. Coaching literature suggests the use of

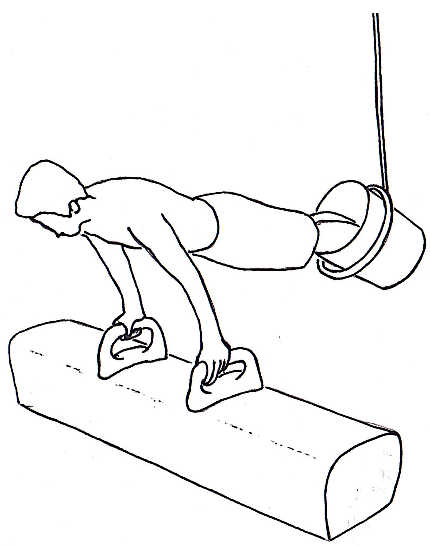

Figure 3-1 Bucket circles on a pommel horse. A gymnast places his legs into a bucket that is suspended from above, and he rotates his legs with the bucket as he performs circles. See Figure 2-1 for the overall motion of circles.

a suspended aid even after acquiring the skill to further improve the quality of circles (Karácsony & Čuk, 1998; Yoshida & Shiroma, 2001). The value of using a suspended aid appears to be its ability to enable gymnasts to experience the desired motion of circles.

What is the ideal motion for circles? In gymnastics, maximizing the movement amplitude is one of the keys to optimal execution (George, 2010). This principle is well applied to circles. The amplitude of circles has been measured mainly in two ways: joint angle or trajectory (Baudry et al., 2009). Baudry and his colleague computed the body segment alignment based on the hip joint angle (Baudry, Leroy, & Chollet, 2003; 2006; Baudry, Leroy, Seifert, & Chollet, 2005; Baudry, Leroy, Thouvarecq, & Choller, 2006). The hip joint angle has also been considered by separating the lateral flexion from the flexion (Fujihara & Fuchimoto, 2006; Fujihara & Gervais, 2010). Another angular variable related to the amplitude of circles is the shoulder angle formed by the trunk and arms. Baudry et al. (2009) found the shoulder hyperextension angle during the rear support phase as one of the amplitude variables of circles.

From trajectory measurements, Grassi et al. (2005) computed the diameter of circles based on the horizontal trajectories of markers attached to the ankles, hips, and shoulders. Baudry et al. (2009) used the same method to compute the diameter of circles, finding significant differences in both the ankle and shoulder diameters between the experts and non-experts. The diameters, computed using the same method, were also used to normalize the standard deviation of the marker trajectories to assess spatial consistency within the movements (Baudry, Seifert, & Leroy, 2008).

In addition to the movement amplitude, the temporal characteristics of circles seem to be related to good-quality circles. According to the previous studies, a gymnast completes a single circle on two handles of the pommel horse in approximately 0.90 – 1.00 seconds (Baudry et al., 2003; 2005; Fujihara, Fuchimoto, & Gervais, 2009; Fujihara & Gervais, 2010; Karácsony & Čuk, 1998; Salmela & Lavoie, 1976; Yamada, Takamatsu, Yokozawa, Hasumi, & Koyama, 2008). No difference in the total duration for a circle has been found between experts and non-experts, but experts tend to have shorter double-support phases and longer single-support phases compared to non-experts (Baudry et al., 2003; Fujihara & Fuchimoto, 2006).

A suspended aid seems to reduce the difficulty in maintaining the dynamic balance during circles, and therefore, gymnasts may be able to concentrate on seeking a better body motion during circles. To the best of our knowledge, however, no study has examined how a suspended aid actually influences the motion of circles in terms of representative kinematic variables, namely, body angles, trajectories, and durations. We hypothesized that the use of the aid does not cause extensive kinematic distortion but some desirable changes such as larger amplitude. It was further hypothesized that the use of the aid might result in a slower tempo. The aim of this paper was to test these hypotheses by investigating the effect of using a suspended aid on the spatio-temporal characteristics of circles.

3.2 Methods

3.2.1 Participants

Eighteen male gymnasts took part in the study. All subjects were able to consistently perform 20 consecutive circles on two handles of a pommel horse. They were at least national level, and four of them had international competition experiences. The mass, height, and ages of the gymnasts were 47.7 ±10.8 kg, 1.55 ± 0.11 m, and 16.2 ± 3.6 years (mean ± standard deviation). They had 9.4 ± 2.9 years of experience in competitive gymnastics and trained 20.3 ± 3.5 hours per week at the time of data collection. All gymnasts had experience in practicing circles with some form of suspended aid but not with the particular aid used in this study. No participant reported any wrist problem that would exclude him from participation in the study. Written informed consent was obtained of all the gymnasts. Prior to the start of this project, ethical approval was obtained through our institutional research ethics review board.

3.2.2 Experimental setup

A no-leg pommel horse (Spieth Anderson International Inc.) was cut in half, and each half was fixed to a force plate (AMTI, OR6-6-4000), which was bolted to the laboratory floor. A 5 mm gap between the two pieces of the horse ensured that forces applied on each half of the horse were measured independently of each other. The pommel reaction forces were used to find manual contact and release. Note that the pommel reaction forces are discussed in the next paper that focused more on the kinetic aspects of circles.

A motion capture system (Qualisys Motion Capture Systems) with 13 cameras (ProReflex MCU 240, f6 lens, Qualisys AB, Sweden), which had the image sensor resolution of 658 (horizontal) by 496 (vertical) pixels, was used for the kinematic data collection. The cameras were placed around the pommel horse using overlapping fields of view in an orientation that assured that any marker was visible to a minimum of two cameras during the performance of circles (Figure 3-2). As a result of a wand calibration, the system-reported standard deviation of the wand length (750.2 mm) was 1.6 mm. Before and after all data collection sessions, we performed the inter-marker-distance accuracy tests by

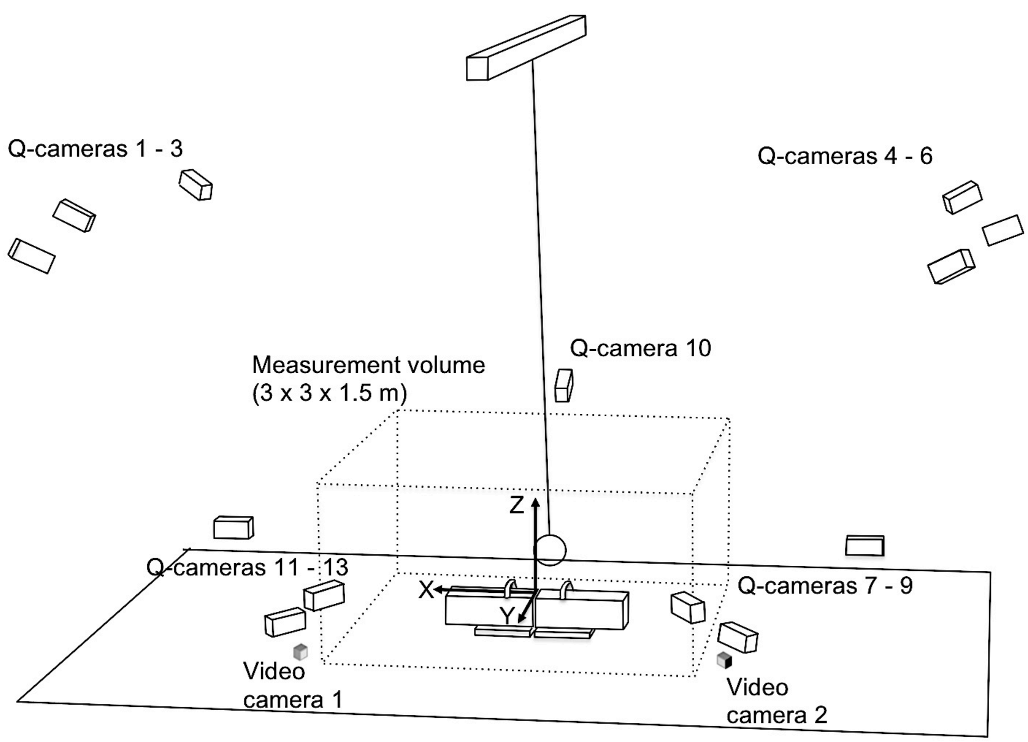

Figure 3-2 The experimental setup. A floor pommel horse was cut in half, and each half was fixed to a force plate. Thirteen Qualisys motion capture cameras (Q-cameras) and two video cameras were positioned around the pommel horse.

moving the same wand in the calibrated measurement volume for 10 seconds. At the least accurate case of all tests, the standard deviation of the wand length was 1.3 mm, the wand length range was 8.3 mm, the 95% confidence interval of the mean error was 1.0 ± 0.1 mm. The origin of the global coordinate system was set at the centre of the top surface of the horse. The X-axis was defined along the horizontal long axis of the horse. The Y-axis was perpendicular to the X-axis on the horizontal plane. The Z-axis was perpendicular to the XY-plane and through the system's origin. The positive directions of the X-, Y-, and Z-axes were rightward, forward, and upward with respect to the direction of the performance.

The force data were sampled with the motion capture system via an analog board (USB1616FS, Measurement Computing Corporation). The system started recording all data at the same time. The sampling rate of the motion capture was 100 Hz, and force data were sampled ten times per frame, that is, at 1000 Hz.

3.2.3 Data collection

After general and event-specific warm-ups, the gymnasts were fitted with lightweight retro-reflective makers as shown in Figure 3-3, and the anatomical calibrations were conducted prior to the main trials. The anatomical landmarks selected were based on the adjusted Zatsiorsky and Seluyanov's data (de Leva, 1996) for estimating body segment parameters. To remove the possible error related to inter-individual reliability, a single experimenter placed the markers on all gymnasts. The gymnasts stayed in the rear support position in the measurement volume for three seconds using a supporting block under their feet, and the three-

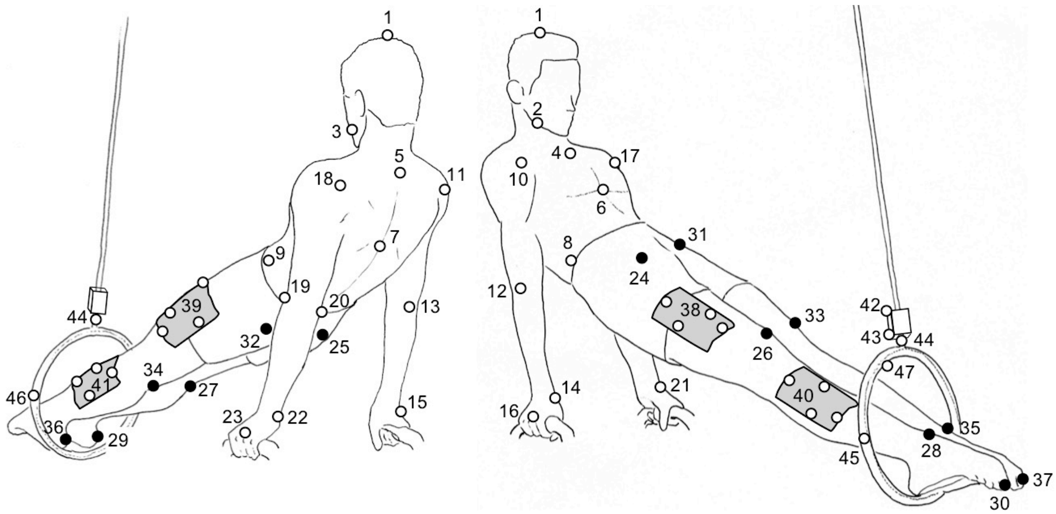

Figure 3-3 Marker placements. The markers from 24 to 37 (filled circles) were removed after anatomical calibrations. Joint centres were estimated as the centre of two surface markers (A & B) except for hip joint centres, which were estimated using Halvorsen's algorithm (2003).

dimensional (3-D) coordinates of the markers were recorded. The hip joint centre was estimated using Halvorsen's algorithm (2003), and all other joint centres were estimated as the middle of two surface markers. As soon as an anatomical calibration session was finished, all markers placed on the anatomical landmarks of the lower extremities (No. 24 – 37 in Figure 3-3) were removed, leaving the four cluster marker sets.

The gymnasts performed three sets of 10 circles on the pommel horse in two conditions: without the aid and with the aid. Either condition was randomly assigned for the first three sets of 10 circles, and then the gymnasts performed another three sets of 10 circles in the other condition. The aid was fixed around a gymnast's ankles using an elastic wrap to assure its location remained fixed on the legs during the trials. To maximize the experimental efficiency, the order of trials was not randomized within a subject. The gymnasts were instructed to practice as much as they needed, but no gymnast practiced more than 30 circles for any condition. They were asked to perform circles as they do in usual training, and no specific instruction about performance was given so that any possible learning effect was minimized. Between each trial, the gymnasts were given as much rest as they needed to reduce the influence of fatigue.

3.2.4 Definition of the phases of circles

In this study, all data were considered to be counter clockwise circles to avoid any potential confusion related to the different circle direction. When a gymnast performs clockwise circles, the sign of the X-coordinates for all data points were inverted. The counter clockwise circles were divided into four functional phases based on hand contacts and releases. The front support phase occurs from the position where the gymnast re-grasps the left pommel to the position where the gymnast releases the right pommel. Likewise, the entry phase, the rear support phase, and the exit phase are defined based on the associated body positions for hand contacts and releases, as illustrated in Figure 3-4.

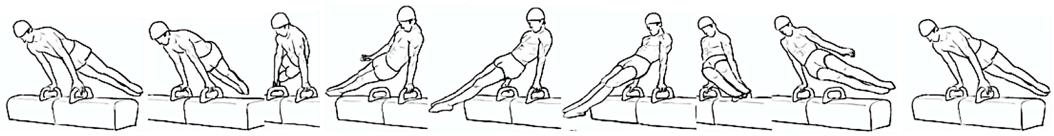

Figure 3-4 Four phases of circles based on hand contact and release. The front support and rear support phases were double-support phases. Conversely, the entry and exit phases are single-support phases.

3.2.5 Data analysis

The 3-D coordinate data were smoothed using a fourth-order Butterworth digital filter (Robertson & Dowling, 2003). The optimal cut-off frequency for each marker displacement, determined by Yokoi and McNitt-Gray's algorithm (1990), ranged from 2.4 Hz to 11.6 Hz. The 3-D coordinates of the anatomical landmarks on the lower extremities were reconstructed based on the coordinates of the cluster markers using the least square method (Cappozzo & Cappello, 1997). Temporal characteristics of the circles were analysed using the 3-D time-histories of the force data. The force data were smoothed at 100 Hz using a Butterworth digital filter.

For angular computations, two local reference systems were defined using a vector product (Fujihara & Gervais, 2010). In the hip reference system (Figure 3-5), the projected angles between the lower trunk (xiphion– the centre of hips) and the thigh (the centre of hips – the centre of knees) on the xz- and on the yz-planes were defined as the lateral-flexion and the flexion of the hip, respectively. Likewise, the projected angles between the upper trunk (suprasternale – xiphion) and the lower trunk (xiphion – the centre of hips) on the xz-plane and on the yz-plane in the trunk reference system were defined as the lateral-flexion and the flexion of the trunk, respectively. Finally, the body angles were determined as the sum of the trunk and hip angles. The trunk reference system was also used for computing shoulder angles formed by the upper trunk segment and the upper arm segments. The adduction-abduction and flexion-extension angles were determined as the projected angles of these segments on the xz-plane and yz-plane, respectively. For flexion-extension angles in the double-support phases, the right and left shoulder angles were averaged. In addition to these angles, the arm segment angle (shoulder – wrist) with respect to the horizontal plane was computed to examine how much gymnasts leaned on their arms while supported.

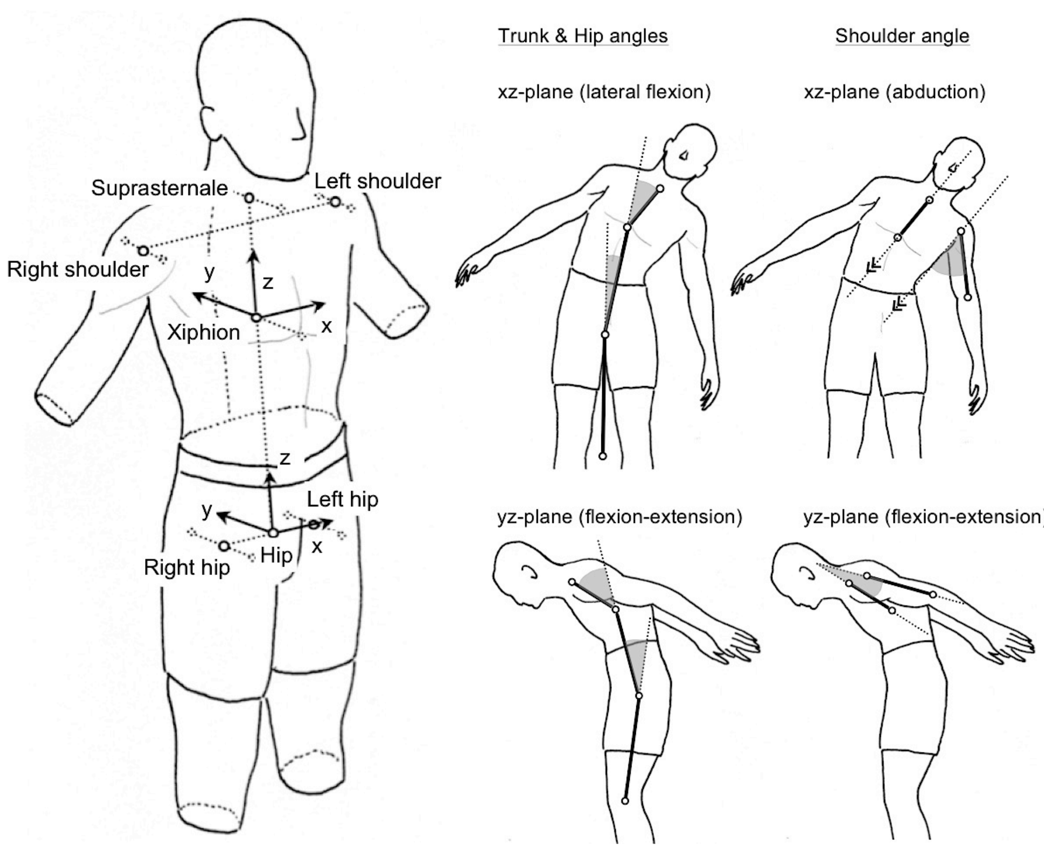

Figure 3-5 The definitions of the local reference systems and angles. The trunk and hip reference systems were defined using the vector cross product.

The diameters of the horizontal rotation were determined by Grassi et al.'s method (Grassi et al., 2005). For example, the radius of the ankle's rotation at each frame was computed as the horizontal distance between the ankle position at each time frame and the centre of the rotation, which was computed as the average ankle position of the all frames. A diameter was computed for each frame, and the mean of all frames was defined as the diameter for the circle. The ankle diameter was based on the trajectory of the centre of the ankles, and the shoulder diameter was based on the trajectory of the suprasternale.

3.2.6 Statistical analysis

Seven circles out of 10, excluding the first two and the last one, were used so that the mean data for each variable were computed from the data of 21 circles (3 x 7 circles). Note that all discrete values were found for each single circle then averaged. Averaging data was justified by reporting standard error of measurement (Stratford & Goldsmith, 1997) for each variable as a reliability index. To examine the influence of using the aid, circles with no aid were compared to circles with the aid. To find the variables that showed practical significance, the dominance statistic—Cliff's *d*—(Cliff, 1993) was computed as an effect size measure for each comparison. The Wilcoxon signed-rank test was performed for 16 discrete variables, which showed the minimum 0.50 of Cliff's *d*. The experiment-wise error rate was set at $p < 0.0250$, and after the Holm's correction for 16 univariate statistical tests, a critical p value for each test ranged from 0.0016 to 0.0250 (Knudson, 2009). All statistical significance tests were performed using PASW Statistics 18.0 (SPSS Inc., 2009).

3.3 Results

3.3.1 Body angles

In general, the gymnasts presented the smaller body flexion during circles with the aid than without (Table 3-1). The greatest difference was found in the front support phase, where the gymnasts actually showed an “arched” body (hyperextension) with the aid. Differences in the body flexion angle were also found during the entry and exist phases; however, there was no practical significance during the rear support phase. The body lateral flexion angles were

Table 3-1 Body angles during circles with the aid and circles without the aid.

Variables (unit)	Trials	SEM	Range	Mean ± SD	Mean Difference	Cliff's *d*	*z-statistic (p)*
Body flexion (°)							
Front support	Aid No aid	4 3	- 40 – - 4 - 17 – 20	- 16 ± 10 3 ± 8	- 19	- 0.90	- 3.73 (0.0002)*
Entry	Aid No aid	3 2	- 25 – 15 - 9 – 29	3 ± 9 11 ± 10	- 8	- 0.50	- 3.41 (0.0006)*
Rear support	Aid No aid	4 3	1 – 41 - 3 – 48	26 ± 10 23 ± 14	3	0.19	No test
Exit	Aid No aid	4 4	- 14 – 22 - 6 – 49	8 ± 9 23 ± 16	- 15	- 0.62	- 3.40 (0.0007)*
All	Aid No aid	2 2	- 20 – 16 - 2 – 35	4 ± 8 15 ± 11	- 11	- 0.58	- 3.50 (0.0005)*
Body lateral flexion (°)							
Entry	Aid No aid	2 2	35 – 52 34 – 54	44 ± 5 42 ± 5	2	0.23	No test
Exit	Aid No aid	3 3	25 – 47 29 – 58	40 ± 6 43 ± 8	- 3	- 0.23	No test

SEM = standard error of measurement, SD = standard deviation
The *z*-statistic (Wilcoxon signed-rank test) was computed for only variables that showed practical difference (Cliff's $d > 0.50$ or Cliff's $d < -0.50$).
The star marks indicate the statistical significance.
The negative value in the body flexion indicates the extension. The direction of the body lateral flexion is rightward in the entry and leftward in the exit.

similar in both circles with and without the aid.

When the hip and trunk angles were examined separately, it became clear that the smaller body flexion resulted primarily from the smaller hip flexion angle, with the exception of the rear support. The mean differences in the hip flexion angle were - 13° in the front support phase, - 8° in the entry phase, and - 14° in the exit phase. The mean differences in the trunk flexion angle were - 6° in the front support phase, 0° in the entry phase, and - 1° in the exit phase. In the rear support phase, however, the smaller hip flexion angle (- 5°) was offset by the greater trunk flexion (8°), resulting in only a 3° difference in the combined body flexion angle. In fact, the difference in the trunk flexion during the rear support showed statistical significance between circles with and without the aid (Cliff's $d = 0.54$, $z = 3.72$, $p = 0.0002$).

3.3.2 Shoulder angles

With the aid, the gymnasts had greater shoulder angles throughout the circle (Table 3-2). The greatest difference was found in the rear support. On average, the hyperextension angles during the rear support were 36° with the aid and 18° without the aid. The flexion angle in the front support and the abduction angles in the single-hand support phases were also larger during circles with the aid. In other words, the gymnasts maintained more space between their arms and trunk in all phases of circles with the aid.

There was no large difference in the arm angle with respect to the horizontal plane. Except for the slight difference found in the front support, the

Table 3-2 Shoulder angles and arm-leaning angles during circles with the aid and circles without the aid.

Variables (unit)	Trials	SEM	Range	Mean ± SD	Mean Difference	Cliff's *d*	*z-statistic (p)*
Shoulder angles (°)							
Front support	Aid	2	21 – 44	32 ± 6	9	0.72	3.73 (0.0002)*
	No aid	2	13 – 34	23 ± 5			
Entry	Aid	2	- 2 – 11	4 ± 5	10	0.76	3.73 (0.0002)*
	No aid	2	- 24 – 2	- 6 ± 9			
Rear support	Aid	2	25 – 48	36 ± 6	18	0.94	3.73 (0.0002)*
	No aid	3	6 – 32	18 ± 8			
Exit	Aid	2	2 – 21	8 ± 9	7	0.84	3.73 (0.0002)*
	No aid	1	- 5 – 7	1 ± 3			
Arm leaning angles (°)							
Front support	Aid	1	56 – 68	62 ± 3	4	0.77	3.42 (0.0006)*
	No aid	1	56 – 61	58 ± 1			
Entry	Aid	1	61 – 78	68 ± 4	2	0.23	No test
	No aid	1	62 – 72	66 ± 3			
Rear support	Aid	4	67 – 79	74 ± 3	3	0.43	No test
	No aid	3	68 – 77	71 ± 3			
Exit	Aid	3	63 – 79	70 ± 4	3	0.44	No test
	No aid	2	62 – 71	67 ± 3			

SEM = standard error of measurement, SD = standard deviation
The *z*-statistic (Wilcoxon signed-rank test) was computed for only variables that showed practical difference (Cliff's $d > 0.50$ or Cliff's $d < -0.50$).
The star marks indicate the statistical significance.

gymnasts' arms generally leaned approximately the same amount regardless of the use of the aid. This implied that the horizontal rotation of the shoulders were similar in both conditions.

3.3.3 Diameters

A clear difference was found in the ankle diameter between circles with and without the aid. The mean ankle diameter, without the aid, was close to an individual's body height (98%). The ankle diameter increased to 115% with the aid (Table 3-3). The 1.0 value of the Cliff's *d* indicated that no circle without the aid had a larger ankle diameter than circles with the aid, when it was normalized

Table 3-3 Ankle and shoulder diameters during circles with the aid and circles without the aid.

Variables (unit)	Trials	SEM	Range	Mean ± SD	Mean Difference	Cliff's *d*	*z-statistic (p)*
Ankle diameter (%height)	Aid	2	109 – 122	115 ± 4	17	1.00	3.73 (0.0002)*
	No aid	1	94 – 103	98 ± 3			
Shoulder diameter (%height)	Aid	1	20 – 32	27 ± 3	- 2	- 0.44	No test
	No aid	1	26 – 32	29 ± 2			

SEM = standard error of measurement, SD = standard deviation
The *z*-statistic (Wilcoxon signed-rank test) was computed for only variables that showed practical difference (Cliff's $d > 0.50$ or Cliff's $d < -0.50$).
The star marks indicate the statistical significance.

to an individual's body height. In contrast to the mean ankle diameter, no practical significance was found in the mean shoulder diameter between the two conditions.

3.3.4 Temporal characteristics and hand contact-release positions

Circles were performed more slowly with the aid. A single circle took 0.93 seconds on average without the aid, whereas it took 1.67 seconds with the aid (Table 3-4). The range was large with the aid. However, regardless of the gymnasts, every single circle with the aid had a longer duration than any circle performed without the aid.

Although the hand-contact positions were very similar, the gymnasts tended to release their hands at an earlier position during circles with the aid than without. In relation to this tendency, circles with the aid showed slightly larger proportion for the single-support phases and smaller proportion for the double-support phases. The difference in the hand-release position was greater in the left hand (16°) than in the right hand (10°), contributing to the statistically significant difference in the ratio of the rear support and the exit phases. However, the difference in the ratio of each phase was not as evident as the difference in the total duration.

Table 3-4 Temporal characteristics and hand contact-release positions of circles with the aid and circles without the aid.

Variables (unit)	Trials	SEM	Range	Mean ± SD	Mean Difference	Cliff's *d*	*z-statistic (p)*
Total Duration (s)	Aid	0.09	1.38 – 2.30	1.67 ± 0.26	0.74	1.00	3.73 (0.0002)*
	No aid	0.02	0.87 – 0.99	0.93 ± 0.03			
Phase proportion (%)							
Front support	Aid	1.9	15.4 – 25.9	18.4 ± 2.9	- 2.1	- 0.43	No test
	No aid	1.5	16.1 – 29.3	20.5 ± 3.2			
Entry	Aid	2.3	28.3 – 38.0	33.9 ± 2.6	1.7	0.41	No test
	No aid	1.9	29.1 – 36.7	32.2 ± 2.4			
Rear support	Aid	1.8	9.9 – 18.4	13.3 ± 2.3	- 2.8	- 0.72	- 3.42 (0.0006)*
	No aid	1.4	13.8 – 18.9	16.1 ± 1.5			
Exit	Aid	2.0	29.6 – 38.3	34.4 ± 2.5	3.1	0.62	3.68 (0.0002)*
	No aid	1.6	26.1 – 35.6	31.3 ± 2.2			
Contact-release position (°)							
LH contact	Aid	7	302 – 339	321 ± 9	1	0.09	No test
	No aid	7	305 – 335	320 ± 9			
RH release	Aid	5	25 – 47	36 ± 6	- 10	- 0.77	- 3.73 (0.0002)*
	No aid	4	34 – 62	46 ± 7			
RH contact	Aid	8	132 – 157	144 ± 7	2	0.14	No test
	No aid	7	131 – 155	142 ± 5			
LH release	Aid	6	192 – 217	206 ± 6	- 16	- 0.96	- 3.73 (0.0002)*
	No aid	6	212 – 231	222 ± 6			

SEM = standard error of measurement, SD = standard deviation, LH = left hand, RH = right hand
The hand contact-release positions were shown as the projected angle of the total leg segment (hip centre – ankle centre) on the horizontal plane (the negative y axis = 0°).
The *z*-statistic (Wilcoxon signed-rank test) was computed for only variables that showed practical difference (Cliff's $d > 0.50$ or Cliff's $d < - 0.50$).
The star marks indicate the statistical significance.

3.4 Discussion

3.4.1 The influence of the suspended aid on the motion of circles

The results of this study confirmed that the use of the suspended aid influenced the motion of the circles. Circles with the aid were generally characterized by smaller body flexion angles, greater shoulder angles, a greater ankle diameter, earlier hand releases, and a longer total duration. On the other hand, the body lateral flexion angles, the arm-leaning angles, and the shoulder diameter remained relatively similar to circles without the aid.

Figure 3-6 illustrates the angular differences between circles with and without the aid. In the front support phase, the body was more extended, and the shoulders were more flexed with the aid than without. In the entry phase, the gymnasts showed a similar degree of the body lateral flexion with the aid, but a larger left-shoulder abduction angle. In the rear support, the difference in the shoulder angle became the greatest of four phases. In the exit phase, the right-shoulder abduction angle increased with the aid. Although it is difficult to discern visually in Figure 3-6, the body flexion angle also decreased in the entry and exit phases. These differences collectively contributed to the larger mean diameter of the ankles.

A primary reason for the use of a suspended aid is to allow gymnasts the opportunity to experience the desired motion of circles. The results of this study showed that circles performed with the aid approach what may be considered desirable in terms of amplitude. Baudry et al. (2009) identified four variables to assess the amplitude of circles: the body segment alignment, the shoulder extension angle during the rear support, the diameter of ankles, and the diameter of shoulders. The body flexion angles were decreased with the aid. The shoulder extension angle in the rear support and the ankle diameter were increased with the aid. Furthermore, the ratio of the single-support phases was slightly increased with the aid, similar to what has been observed in experts (Baudry et al., 2003; Fujihara & Fuchimoto, 2006). These changes seem preferable in terms of the kinematics of circles.

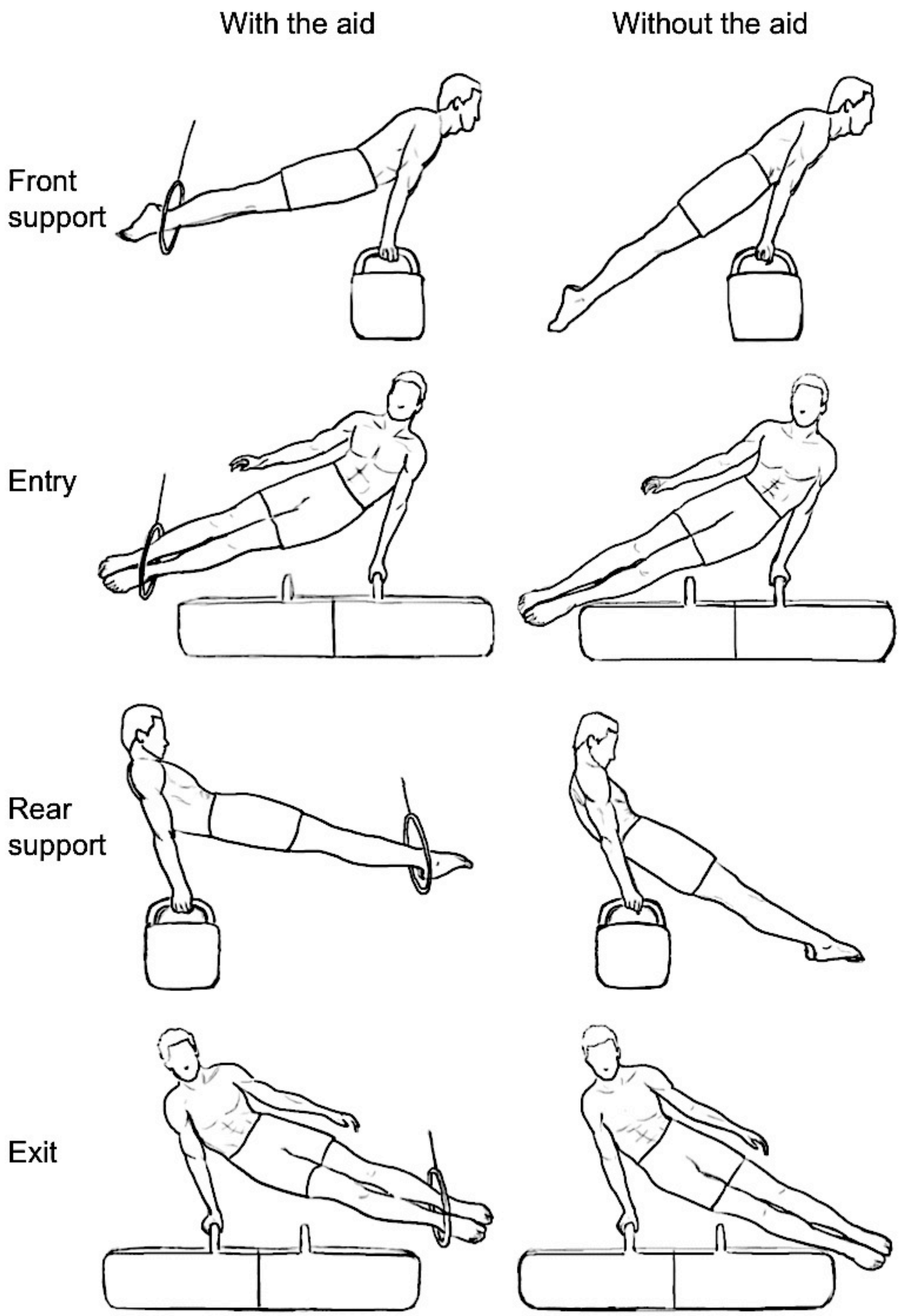

Figure 3-6 The illustrative comparison of circles with the aid and without the aid. The illustrations were based on the averaged results shown in the Table 3-1 and 3-2.

Importantly, the shoulder diameter remained unchanged despite achieving such a high body position with the greater shoulder angles and the smaller body flexion angles. Fujihara (2010) argued that a higher mass-centre rotation would result from the greater centrifugal force, which requires greater centripetal force. The horizontal component of the pommel reaction forces is responsible for producing the necessary centripetal forces during circles (Fujihara et al., 2009). The direction of force vectors from the pommels generally corresponds to the arm segment angle (Fujihara et al., 2009). Therefore, such a high rotation of the body would be associated with the greater leaning arms and the larger shoulder diameter. With the suspended aid, the gymnasts had a support at their ankles, making seemingly unrealistic movement amplitude possible.

Another unrealistic aspect was the slowness of circles. The slower circles might be associated with our limited information-processing capacity, one of the main factors in determining the speed of circles (Salmela & Lavoie, 1977). With the aid, a gymnast can slow down easily without losing the dynamic balance necessary to perform circles. That is, the gymnasts could perform circles at a comfortable speed for their continuous error-correction processing. Also, the moment of inertia about the mass centre was increased by the additional mass (i.e. the aid) at the distal segment. For this reason, it would be hard for gymnasts to do circles with the aid faster than circles without the aid, even if gymnasts were instructed to perform circles at their maximal speed.

3.4.2 The implication and limitation of the study

The suspended aid was shown to be helpful for gymnasts to experience a more desired motion of circles in terms of amplitude, so it can be used as a training aid for kinematic assistance. In gymnastics training, spotting is indispensable and is used for a variety of purposes (Sands, 1996). Kinematic assistance is one of these purposes, and it can be defined, in this context, as physical assistance that can make it possible for a gymnast to perform a skill or a desired motion in the process of learning. Direct spotting by a coach is not a common practice for learning circles due to the nature of its movement, but a suspended aid could “spot” a gymnast. A suspended aid helps them experience a desired motion or free attention for focusing on any specific aspect of circles in the process of learning.

Several limitations of this study should be addressed here. First of all, the actual influence of a suspended aid on motor learning was beyond the intended scope of this study. The influence of kinematic assistance on complex-skill learning is still controversial (Wulf & Shea, 2002). Second, the results were based on only one type of a suspended aid. Most subjects reported that circles with the aid developed for this study were easier than so-called bucket-circles. With a different variation of suspended aids, the motion of circles might vary. Especially, the height of the aid might have a large influence on the kinematics because it almost solely determines the height of the ankles during circles. Consequently, gymnasts would accommodate the body and shoulder angles to the prescribed positions of the legs. In this study, it was set as low as possible while avoiding the collision between the aid and the pommel horse. If circles are practiced on a pedagogical apparatus such as mushroom, an aid can be set lower.

3.5 Conclusions

When circles were performed with the suspended aid, the amplitude of circles was increased. This means that the aid functioned as spotting, which is often used by a gymnastics coach to let gymnasts experience a more desirable motion of a skill. Together with the following study focusing on a kinetic comparison, the effects of a suspended aid on circles technique are more thoroughly understood.

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Chapter 4

Circles with a Suspended Aid Part III:
Mass-centre Rotation and Hip Joint Moment

4.1 Introduction

This chapter examined circles with the suspended aid more from a kinetic viewpoint. Due to the complexity of the motion and possible methodological difficulties, there has not been much research on the kinetics of circles. Nevertheless, two different kinds of approach can be found in the literature: analysing the mass-centre motion in relation to the external forces (i.e. pommel reaction forces) and analysing a joint moment profile.

Fujihara, Fuchimoto, and Gervais (2009) recorded the pommel reaction forces on each hand separately and simultaneously using a pommel horse model that included two force plates. They confirmed that the vertical component of the pommel reaction forces is responsible for supporting body weight and up-and-down movement of the body to pass over the horse. The horizontal components, on the other hand, act as the centripetal force and the tangential accelerative force for the rotational movement of the mass centre. Fujihara et al. (2009) used both kinematic and kinetic data to conclude that the horizontal rotation of circles consists of two kinds of rotations. During the single-support phases, the whole body is rotating mainly about the supporting arm, and during the double-support phases, the body is rotating mainly about its mass centre.

In terms of joint moment profiles during circles, only two studies are currently available. First, de Leva (1997) attempted to analyse shoulder joint moments during circles by simulation. For the sake of computational simplicity, he assumed that a gymnast's body was composed of two rigid segments—body and arm—and that a gymnast was in the front support position throughout a whole rotation. These assumptions might be too simplistic, but it is also true, at least to date, that circles may be too complicated to be simulated with reasonable assumptions. Second, Fujihara and Gervais (2009) computed hip joint moments during circles. Considering that gymnasts keep their legs straight and together, they assumed that the lower extremities moved as a single rigid body. Under this assumption, moments at each side of the hips cannot be determined. Nevertheless, this method was still useful when analysing overall hip motions. The results implied that the lateral flexion at the hips is an important feature of circles.

The purpose of this study was to investigate the influence of using the suspended aid on circle kinetics. More specifically, this paper attempted to answer questions of whether or not the use of a suspended aid influences the rotational mechanics of the whole-body mass centre and whether or not the use of a suspended aid alter the hip moment profiles during circles.

4.2 Methods

This study's data collection protocol has in large part been described in chapter three. Only the additional methods for the kinetic analysis are described here.

4.2.1 Measuring and processing force data

In addition to the pommel reaction forces measured by the two force plates set under the pommel horse, the cable tension was measured with a single-axis load transducer (LCCB-500, Omega Engineering Inc.) embedded between the cable and the twisting belt. The load transducer was calibrated by suspending known weights (5, 10, 15, 20, 40, 80, 100 lbs. = 22.2, 44.5, 66.7, 89.0, 178.0, 356.0, 445.0 N). The obtained regression equation consistently showed a high linearity ($R^2 \geq 0.9996$) over the time of data collection. All force data output from the force plates and the load transducer were recorded with the motion capture system via an analog board (USB-1616FS, Measurement Computing). All force data were sampled at 1000 Hz, smoothed at 100 Hz using a fourth-order Butterworth digital filter and scaled to each gymnast's body weight (BW).

4.2.2 Hip joint moment

For the computation of hip joint moments, several assumptions were made. First, all segments of the lower extremities—feet, shanks, and thighs—were assumed to be a single rigid segment, total leg (Fujihara & Gervais, 2009). The moment of inertia of the total leg was determined using the parallel axis theorem based on the six segments. Under this assumption, a hip joint moment for each leg was not considered. Therefore, hip joint moments for adduction at each side of the hip, which was probably present to keep two legs together, was not taken into account. Air resistance was assumed to be negligible. The external force applied to the total leg segment was only gravity and the force applied from the aid (the aid reaction force) during circles.

Using kinematic, anthropometric, and external force data, hip joint moments were estimated by solving Euler's equations (Andrews, 1995) with two rigid bodies: total leg and lower trunk. Three local reference systems, two for the segments and one for the joint, were defined using a vector product as shown in Figure 4-1. In addition to the joint moment profiles, the joint power was computed as the product of the joint moment and the joint angular velocity that was defined as the relative angular velocity of the distal segment with respect to the proximal

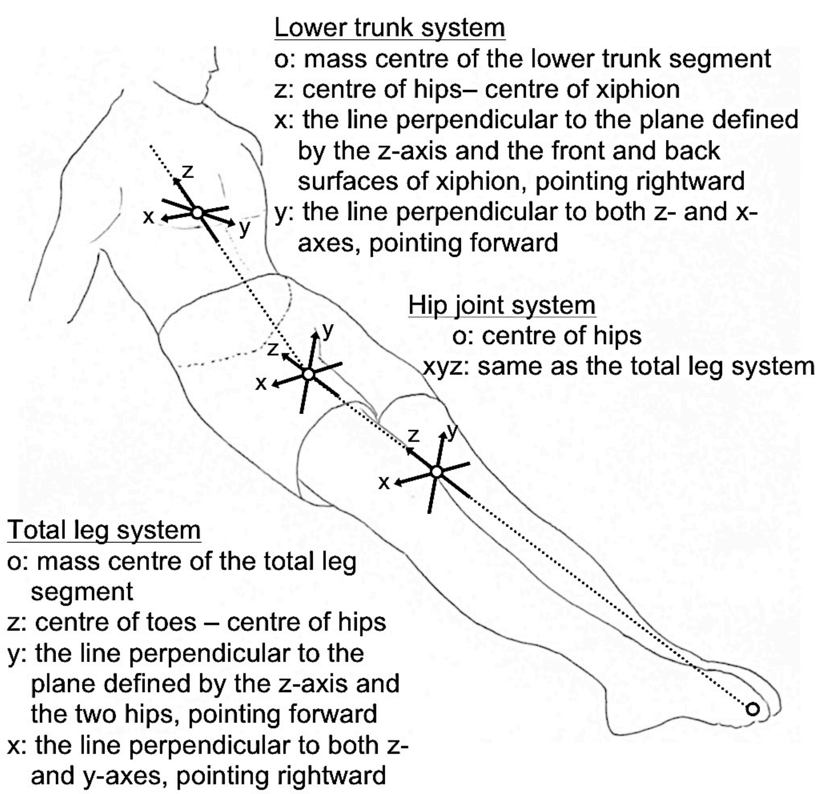

Figure 4-1 The definitions of the local reference systems for joint moment computations.

segment (Hamill & Selbie, 2004). The joint moments and joint powers were normalized by the product of each gymnast's body weight and height (Moisio, Sumner, Shott, & Hurwitz, 2003).

4.2.3 Determining the aid reaction force

To determine the aid reaction force, the inner-ring-fixed local reference system was defined on the aid (Figure 4-2). The inner-ring-fixed reference system had its origin at the centre of the ring frame of the twisting belt, defined as the middle point of marker #45 and marker #46 (see also Figure 3-3 in chapter three). The z-axis was along a line from the origin to marker #47, which was fixed to a part of the inner ring frame. The y-axis was a line perpendicular to the ring-frame

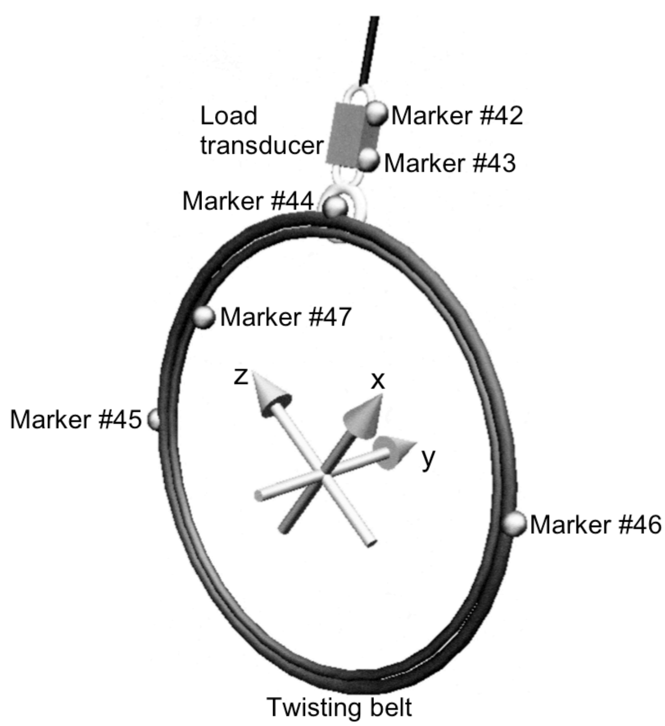

Figure 4-2 The definition of the inner-ring-fixed reference system. The z-axis was defined as a line through the centre of the ring frame to the marker #47, which was attached to the inner ring of the twisting belt. The y-axis was perpendicular to the ring plane. The x-axis was perpendicular to both the z- and y-axes.

plane, and the x-axis was a line perpendicular to both the z- and y-axes.

When the displacements of all markers were transformed into the inner-ring-fixed system, no translation of the twisting belt should be observed during circles; the system was in equilibrium. Therefore, the sum of all forces acting on the ring should be equal to zero along each axis.

$$\sum \vec{F} = \vec{F}_{\text{cable}} + \vec{F}_{\text{leg}} + \vec{F}_{\text{g}} + \vec{F}_{\text{cent}} = 0 \qquad (1)$$

where F_{cable} is the cable tension, F_{leg} is the force applied from the gymnast's legs, F_{g} is the gravitational force for the mass of the aid, and F_{cent} is the centrifugal force for the mass of the aid.

All forces other than the force applied from the legs (F_{leg}) were known variables either from measurements or computations. The cable tension (F_{cable}) was measured using the load transducer embedded within the cable. The line from marker #43 to marker #42 indicated the direction of the force vector. Second, the gravitational force (F_{g}) was simply computed as the product of the mass of the aid (2.3 kg) and the acceleration due to gravity (- 9.81 m/s^2) in the ground reference system. Finally, the centrifugal force (F_{cent}) was a function of the velocity and its rotational radius. That is,

$$\left|F_{\text{cent}}\right| = \frac{mv^2}{r}$$

where m is the mass of the aid, v is the horizontal velocity of the ring frame in the global reference system, and r is the instantaneous radius of the horizontal rotation of the ring frame. By taking the first derivative of the horizontal displacement of the ring frame in the global reference system, *v* was computed. The instantaneous radius (*r*) was determined as the distance between the centre of the aid (the origin of the inner-ring-fixed system) and the instantaneous centre of the horizontal rotation, which was the intersection of two successive normal lines of the rotational path. The direction of the centrifugal force is always along the radius of the rotation. Note that only the centrifugal force due to the horizontal rotation of the twisting belt was considered, and any centrifugal forces caused by the other oscillations was regarded as negligible, because the aid moved in a circular motion almost parallel to the horizontal plane. All these known forces (F_{cable}, F_g, and F_{cent}) were first determined in the ground reference system and then transformed into the inner-ring-fixed reference system. By inserting them into the equation (1), F_{leg} was determined in the inner-ring-fixed reference system and then transformed into the ground reference system.

The point of force application for F_{leg} was assumed to lie on a circle that has the radius *d* in the xz-plane in the inner-ring-fixed reference system. The value of *d* was determined based on a direct measurement during the experiment. Then, the point of force application ($\vec{P}$) for F_{leg} was computed as:

$$\vec{P} = d \times \frac{\overrightarrow{F_{leg}}}{\left|\overrightarrow{F_{leg}}\right|}$$

The last piece of the necessary information was the free moment about the point of force application. The total moment of the ring frame about its centre was computed as:

$$\sum \vec{M} = I \cdot \vec{\alpha}$$

where I is the principal moment of inertia of the ring frame about its centre, and α is the angular acceleration of the ring frame about its centre. By modelling both the outer and inner ring frames together as a simple ring and the inner ring frame solely as another simple ring, the mass moments of inertia were computed as:

$$I_X = I_Z = \frac{1}{4}\left(a^2 + c^2\right)M$$

$$I_Y = \frac{1}{2}\left(a^2 + b^2\right)m$$

where I_X , I_Y, and I_Z are the principal moment of inertia of the ring frame about each axis as shown in Figure 4-2, a is the inner radius of the inner ring frame, b is the outer radius of the inner ring frame, c is the outer radius of the outer ring frame, M is the total mass of the twisting belt (2.1 kg), and m is the mass of the inner ring (0.8 kg). The mass of other parts of the suspended aid such as a bungee rope was considered to be negligible for the moment of inertia calculation. The angular acceleration of the ring frame about the corresponding axes was computed as the time derivative of the angular velocity, which was computed as:

$$\omega_X = k \cdot \frac{dj}{dt}$$

$$\omega_Y = i \cdot \frac{dk}{dt}$$

$$\omega_Z = j \cdot \frac{di}{dt}$$

where ω_X, ω_Y, and ω_Z are the components of the angular velocity of the ring frame about three axes, and i, j, and k are the unit vectors along these axes. The free moment (M') was calculated by subtracting the moments caused by the cable tension and the forces applied from the legs from the total moments. That is:

$$M' = I \cdot \vec{\alpha} - \vec{P}_{\mathrm{PFA}} \times \vec{F}_{\mathrm{leg}} + \vec{P}_{\#44} \times \vec{F}_{\mathrm{cable}}$$

where $\vec{P}_{\mathrm{PFA}}$ and $\vec{P}_{\#44}$ were the position vectors of the point of force application for $\vec{F}_{\mathrm{leg}}$ and marker #44 in the inner-ring-fixed reference system, respectively. The moment caused by the cable tension, which is the last term of the above equation, was negated for computing the free moment about the y-axis because the cable tension does not produce any rotation of the inner ring frame.

When a force is applied from the legs to the aid in the tangential direction of the twisting belt, it causes only pure rotation of the inner ring and no translation of the twisting belt. Therefore, $\vec{F}_{\mathrm{leg}}$ computed in the above method did not reflect any tangential force that caused the rotation of the inner ring. Such a force was reflected in the free moment about the y-axis of the inner-ring-fixed reference system.

4.2.4 Statistical analysis

In terms of statistical procedure, the number of discrete variables that were subject to the statistical significance test was the only difference from chapter three. The Wilcoxon signed-rank test was performed for eight discrete variables, so the critical p value for each test ranged from 0.0031 to 0.0250 after the Holm's correction (Knudson, 2009).

4.3 Results

4.3.1 Mass-centre kinematics

Figure 4-3 shows the trajectories and velocities of the total body mass centre during circles with and without the aid. On the horizontal plane, the shapes of the two averaged trajectories were similar, but the trajectory for circles with the aid had a larger diameter (Table 4-1). Note that Grassi et al.'s method was applied to compute the diameter of the mass-centre rotation as done for the ankle and shoulder in the last chapter (Grassi et al., 2005). The anterior-posterior range of the mass-centre displacement was 0.40 ± 0.04 m (mean ± standard deviation) for the aid trials and 0.24 ± 0.02 m for the non-aid trials (Cliff's $d = 1.00$, $z = 3.73$, $p = 0.0002$). Similarly, the medio-lateral range of the mass-centre displacement was 0.16 ± 0.04 m for the aid trials and 0.08 ± 0.02 m for the non-aid trials (Cliff's $d = 0.96$, $z = 3.73$, $p = 0.0002$).

When the gymnasts performed circles with the aid, they maintained the higher mass-centre position throughout a circle (Figure 4-3 and Table 4-1). The difference in the mass-centre height was the greatest during the rear support (0.47 ± 0.03 m vs 0.36 ± 0.03 m, Cliff's $d = 1.00$, $z = 3.73$, $p = 0.0002$) where the mass centre tended to drop during the no-aid trials.

Despite the greater distance travelled during circles with the aid, the resultant velocity of the mass centre was relatively similar to that for the non-aid trials because of the greater total duration, as shown in chapter three. When the total duration was normalized to 100%, the velocity curve for the aid trials showed a similar shape to that for the non-aid trials (Figure 4-3).

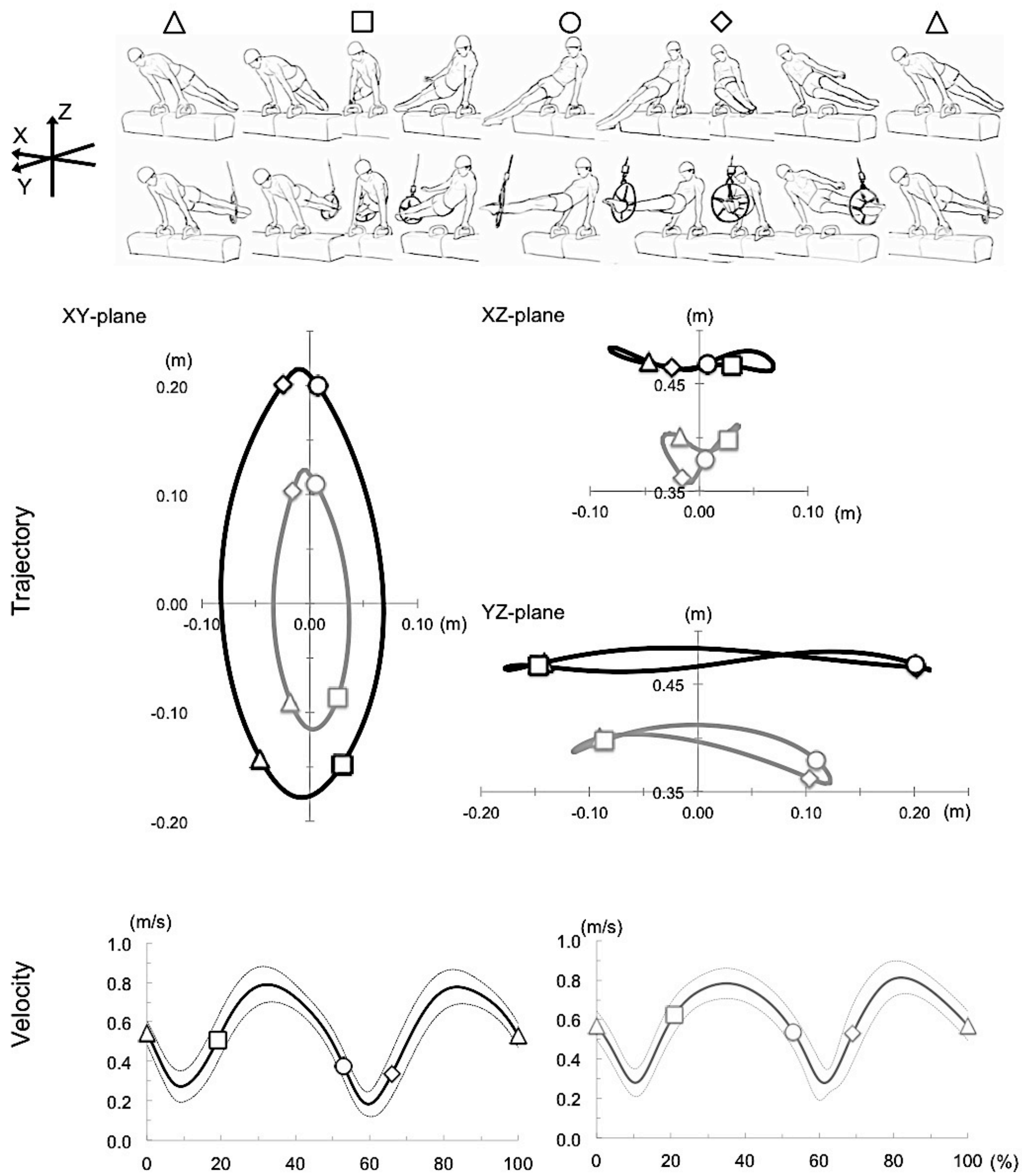

Figure 4-3 The average trajectories and velocities of the mass centre during circles with the aid (black) and without the aid (grey). All graphs were based on the average of 378 circles (18 gymnasts × 21 circles). The time-normalized velocity curves were also shown with the ± 1 standard deviation from the average (broken line). The mass-centre rotation was higher and larger during circles with the aid. Despite its greater distance travelled, the velocity was similar due to a longer duration for a single circle with the aid.

Table 4-1 The mass-centre kinematics during circles with the aid and circles without the aid.

Variables (unit)	Trials	SEM	Range	Mean ± SD	Mean Difference	Cliff's *d*	*z-statistic (p)*
Diameter (%)							
Max	Aid	2	23 – 34	27 ± 4	11	1.00	- 3.73 (0.0002)*
	No aid	1	14 – 18	16 ± 1			
Min	Aid	2	5 – 14	9 ± 3	5	0.96	- 3.73 (0.0002)*
	No aid	1	2 – 7	4 ± 1			
Average	Aid	1	15 – 25	19 ± 3	8	1.00	- 3.73 (0.0002)*
	No aid	0	9 – 12	11 ± 1			
Mean height (m)							
All	Aid	0.00	0.43 – 0.52	0.47 ± 0.03	0.08	0.97	- 3.73 (0.0002)*
	No aid	0.00	0.35 – 0.45	0.39 ± 0.03			
Velocity (m/s)							
Max	Aid	0.05	0.70 – 1.05	0.82 ± 0.09	- 0.02	- 0.19	No test
	No aid	0.04	0.71 – 1.00	0.84 ± 0.08			
Min	Aid	0.03	0.06 – 0.31	0.14 ± 0.06	- 0.05	- 0.51	- 1.52 (0.1284)
	No aid	0.04	0.08 – 0.31	0.19 ± 0.05			
Average	Aid	0.03	0.44 – 0.74	0.55 ± 0.07	- 0.05	- 0.46	No test
	No aid	0.02	0.50 – 0.72	0.60 ± 0.06			

SEM = standard error of measurement, SD = standard deviation
The *z*-statistic (Wilcoxon signed-rank test) was computed for only variables that showed practical difference (Cliff's *d* > 0.50 or Cliff's *d* < - 0.50).
The star marks indicate the statistical significance.

4.3.2 External forces applied to the gymnasts

During circles with the aid, the gymnasts experienced both the aid reaction force and the pommel reaction forces. As shown in Figure 4-4, the aid reaction force did not have a large horizontal component. The maximal value of the vertical aid reaction force was 0.47 ± 0.07 BW, and the mean value over a single circle was 0.28 ± 0.03 BW on average.

The magnitude of the pommel reaction forces was attenuated in all components by the use of the aid. When the xyz-resultant force was regarded as a representative variable, the peak and average forces were attenuated to 62% and 74% of those recorded during the non-aid trials, respectively. Despite the decrease in the magnitude, the force curves were similar in shape except for the vertical

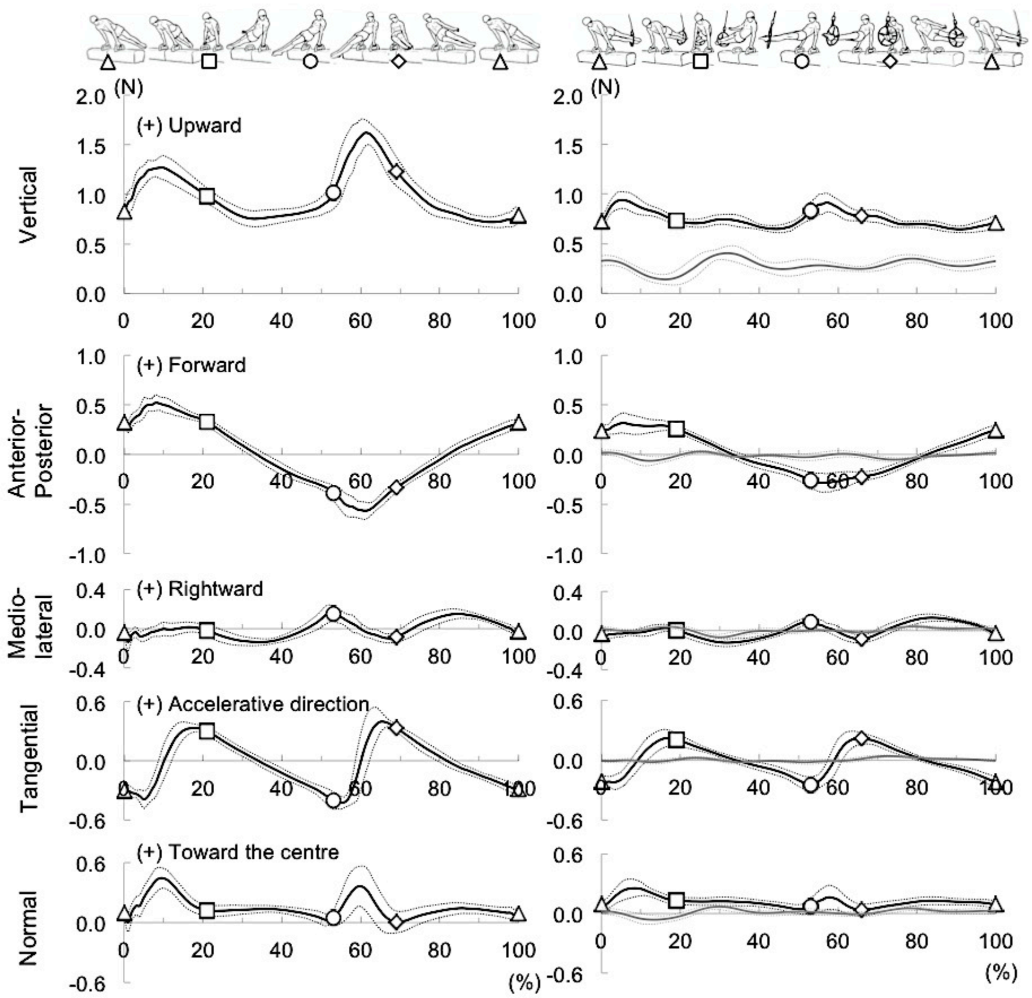

Figure 4-4 The both-hand resultant pommel horse reaction forces (black) and the aid reaction force (grey) during circles without the aid (left) and with the aid (right). The solid lines indicate average of 378 circles (18 gymnasts × 21 circles) and broken lines indicate the ± 1 standard deviation from the average. Note that peak force values were somewhat attenuated due to the time-normalizing and averaging process.

component. Because the force attenuation for the vertical component was dramatic during the double-support phases, in which the large peaks occurred, the force curve was flattened. When the horizontal component was resolved into the tangential and normal components, it was shown that the tangential component was attenuated overall while maintaining the same pattern. On the other hand, the force reduction of the normal component occurred primarily during the double-hand support phases. In general, the direction of the pommel reaction force vectors corresponded to the arm segment lines, except for the medio-lateral component during the double-support phases (Figure 4-5).

4.3.3 Hip joint moment

The hip joint angular velocity profiles showed that the gymnasts had similar hip motions during circles with and without the aid (Figure 4-6). The gymnasts flexed their hip from the late front support phase to the early entry phase with the maximal velocity around the right-hand release. Relatively large standard deviations implied some individual differences. The maximal lateral flexion (the angular velocity = 0) generally occurred during the entry and exit phases when the legs moved toward the pommel horse. The maximal angular velocities for the lateral flexion were seen during the double-support phases. The angular velocity for the long-axial rotation indicated the twisting motion between the leg and trunk segments. Over the front support phase, the total leg segment was axially rotated towards the right with respect to the trunk segment. Then, around the time of right-hand release, the total leg segment was maximally twisted towards the right with respect to the trunk segment. These characteristics were generally consistent even when circles were performed with the aid. However, the variability among the gymnasts was smaller with the aid.

Despite the similarity in the hip motions, a large difference in the hip joint moments was found between circles with and without the aid. The net flexion-

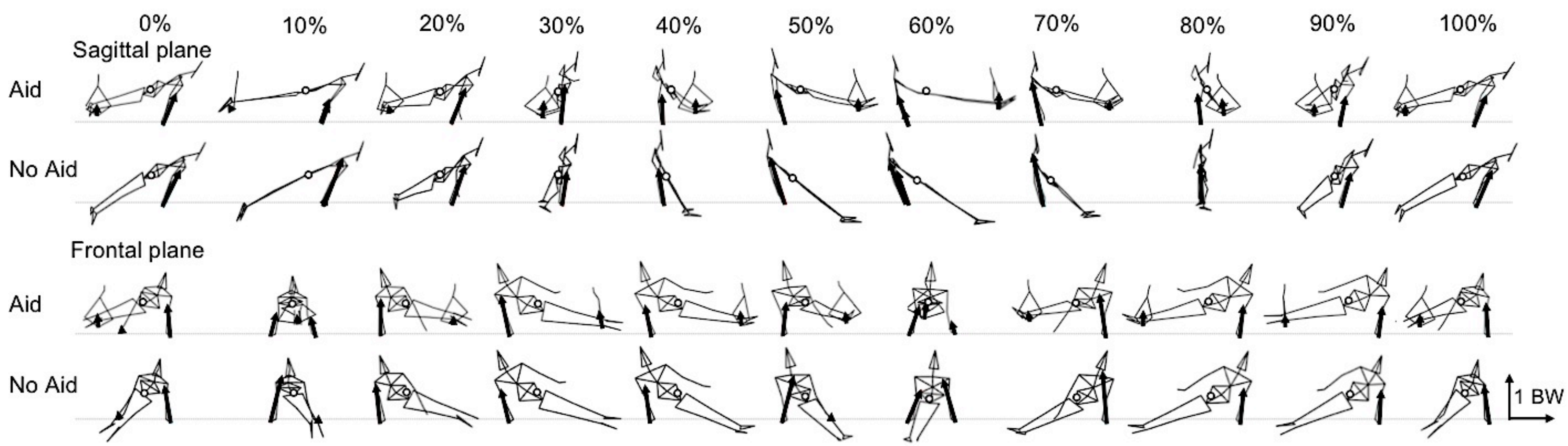

Figure 4-5 The stick figures and the force vectors during a single circle with the aid and without the aid, performed by one of the gymnasts. The open circles indicate the mass centre. This typical example shows that the direction of the pommel reaction force vectors generally corresponds to the line of the arm segments.

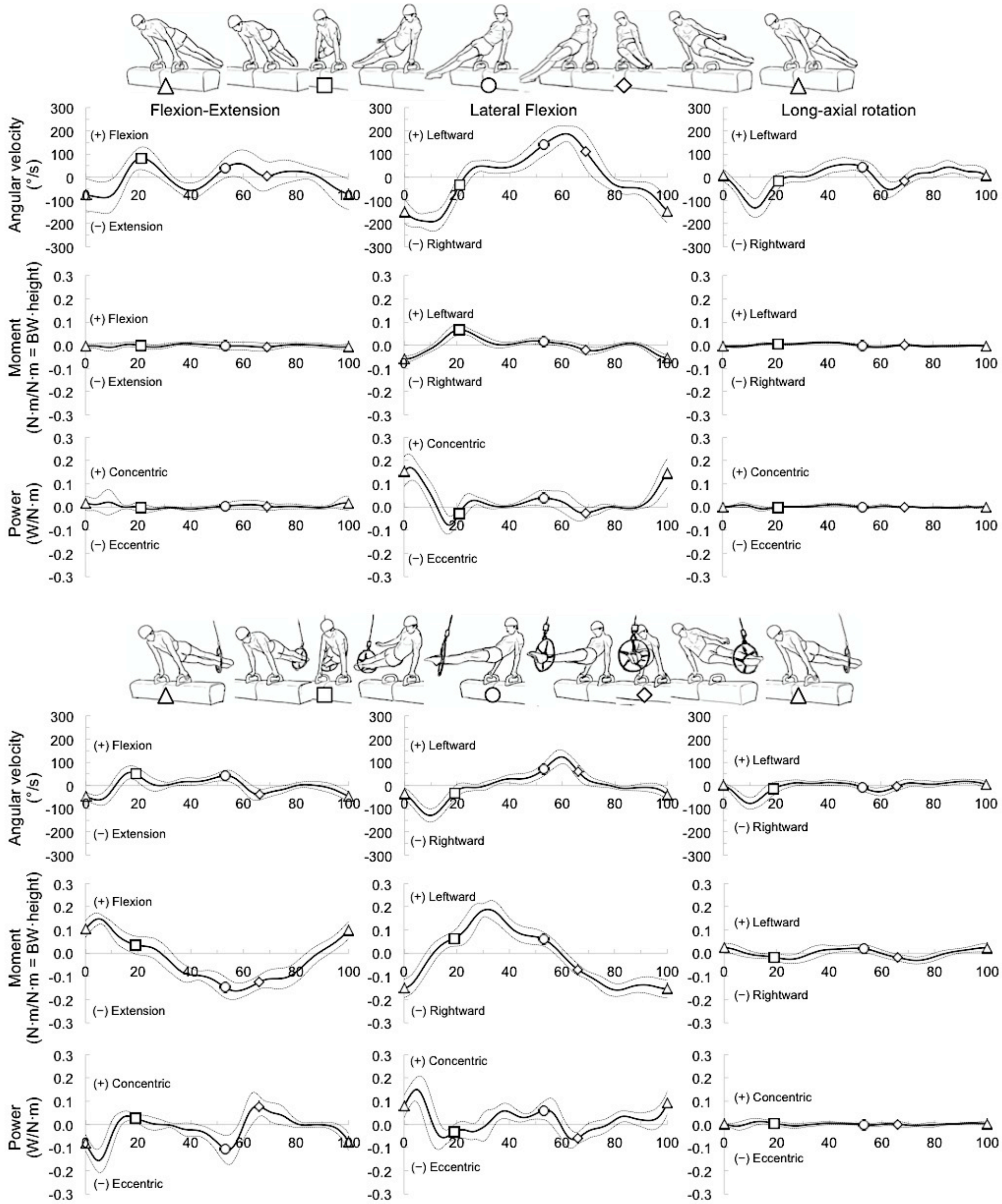

Figure 4-6 Angular velocities, moments, and powers at the hip joint during circles without the aid (top) and with the aid (bottom). The solid lines indicate average of 378 circles (18 gymnasts × 21 circles) and the broken lines indicate the ± 1 standard deviation from the average. Whereas the net flexion-extension moments were nearly zero throughout a circle without the aid, relatively large flexion-extension moments were found during circles with the aid. The difference was also found in the lateral-flexion moments during the entry and exit phases.

extension moment was nearly zero throughout a circle without the aid. With the aid, however, the peak flexion and extension moments were found in the front and rear supports, respectively. Similarly, the peak lateral flexion moments were seen in the entry and exit phases. The flexion moment in the front support was largely eccentric, and the extension moment in the rear support was changed from concentric to eccentric contractions.

4.4 Discussion

4.4.1 The influence of the aid on the mass-centre mechanics

The greater amplitude of the circles with the aid was shown in the mass-centre trajectory. Chapter three showed that the shoulder diameter did not change with the use of the aid despite the large increase in the ankle diameter. Such a body motion was associated with the larger horizontal rotation of the mass centre. Also, the mass centre maintained the higher positions throughout a circle with the aid. If the horizontal rotation of mass centre during circles is modelled as a conical pendulum swing of a particle (Karácsony & Čuk, 1998; Smith, 1982), a greater centrifugal force is necessary for a higher and larger rotation of the particle (Fujihara, 2010). The centrifugal force can be expressed as mv^2/r (m: mass, v: velocity, r: radius of rotation). The radius of rotation in the equation was not the same as the diameter analysed in this study, but the larger radius of rotation can still be implied from Figure 4-3. Thus, circles with the aid had a similar velocity and a larger radius, which would result in the smaller centrifugal force. Therefore, the higher and larger mass-centre rotation during circles with the aid cannot be explained by the centrifugal force. It was possible only because the gymnasts had an additional support with the aid.

In line with the previous study (Fujihara et al., 2009), the pommel reaction force vectors generally corresponded to the arm segment lines. This was observed even in the aid trials. Although the aid reaction force was primarily a vertical force, it contributed to a reduction in the magnitude of all the pommel reaction force components. These results implied that the horizontal component of the pommel reaction forces was produced as a result of the arm segment angles and "pushing" forces along the arms to support body weight. When the magnitude of the resultant pommel reaction force was reduced with the aid, the horizontal component of the pommel reaction force was also attenuated because the direction of the resultant force vector was maintained. As an example, the peak force attenuations in the vertical component during the double-support phases were accompanied by the peak force reductions in the anterior-posterior component (Figure 4-4).

The force reduction in the horizontal component was probably related to the slower circles. The mass-centre velocity becomes very small in the double-hand support phases of circles (Table 4-1), and a body mainly rotates about its mass centre to switch supporting hands (Fujihara et al., 2009; Fujihara & Gervais, 2010). In short, the rotation of the mass centre repeats (almost) stopping, accelerating, and decelerating every half circle. The tangential component of the pommel reaction forces is responsible for increasing the speed of the mass-centre horizontal rotation. Although no significant difference in the mass-centre velocity was found, circles with the aid took longer to reach its maximal value due to the attenuated tangential reaction force. The smaller tangential acceleration can be another explanation for a slower circle as well as the other explanations, namely, the increased moment of inertia and the limited information-processing capacity, discussed in chapter three.

4.4.2 The influence of the aid on the hip joint moment profiles

The results of this study confirmed that the aid had a large influence on the hip joint moments. When the gymnasts performed circles without the aid, the net moment for the flexion-extension motion was very small throughout a circle. This suggested that the gymnasts exerted a similar amount of flexion and extension moment at the hip joint, possibly with an intention to keep their bodies straight. However, a net moment never tells us how strongly the agonists and antagonists co-contracted (Winter, 2009). The greater co-contraction increases the joint stability. The difference in the joint stability might cause the difference in the joint angular motion. On the other hand, when the gymnasts performed circles with the aid, the net hip joint moments changed so that the total legs pushed down on the aid throughout the circle. In the coaching literature “bucket-circles” are recommended to refine circle technique (Karácsony & Čuk, 1998; Yoshida & Shiroma, 2001), but it is anecdotally known that apparently ideal circles with a bucket cannot be directly transferred to circles without it. The difference in the net hip joint moment can partially explain why bucket-circles are different from circles with no aid.

4.4.3 The implications and limitations

On a kinetic level, a suspended aid could be valuable by providing gymnasts with an opportunity to experience a similar weight-bearing pattern with a smaller magnitude on their upper extremities. Such a practice would be useful for a progression to learning a new skill, control of training volume or rehabilitation (chapter two).

What this study can suggest is several technical points that are important whenever a suspended aid is used for any purpose. First, when practicing circles with a suspended aid, gymnasts should be encouraged to increase the rotational speed of the circles so that the temporal characteristics become more similar to circles without an aid. Second, gymnasts should be encouraged to increase shoulder diameter (or arm leaning angles) as their body become straighter. By doing so, circles would become dynamically more balanced by themselves and therefore less dependent on the aid (Figure 4-7). Third, gymnasts should be encouraged to increase the hip joint stability by co-contracting the hip extensors and flexors while keeping a smaller hip flexion angle. Figure 4-8 presents three different situations where the net hip joint moment would be the same. As a gymnast increases the degree of co-contraction, the ratio of moment due to the aid reaction force decreases. In other words, the relative influence of the aid reaction force on the moment equation decreases. Then, whereas the net moment remains the same, the muscle force activation pattern probably becomes more similar to

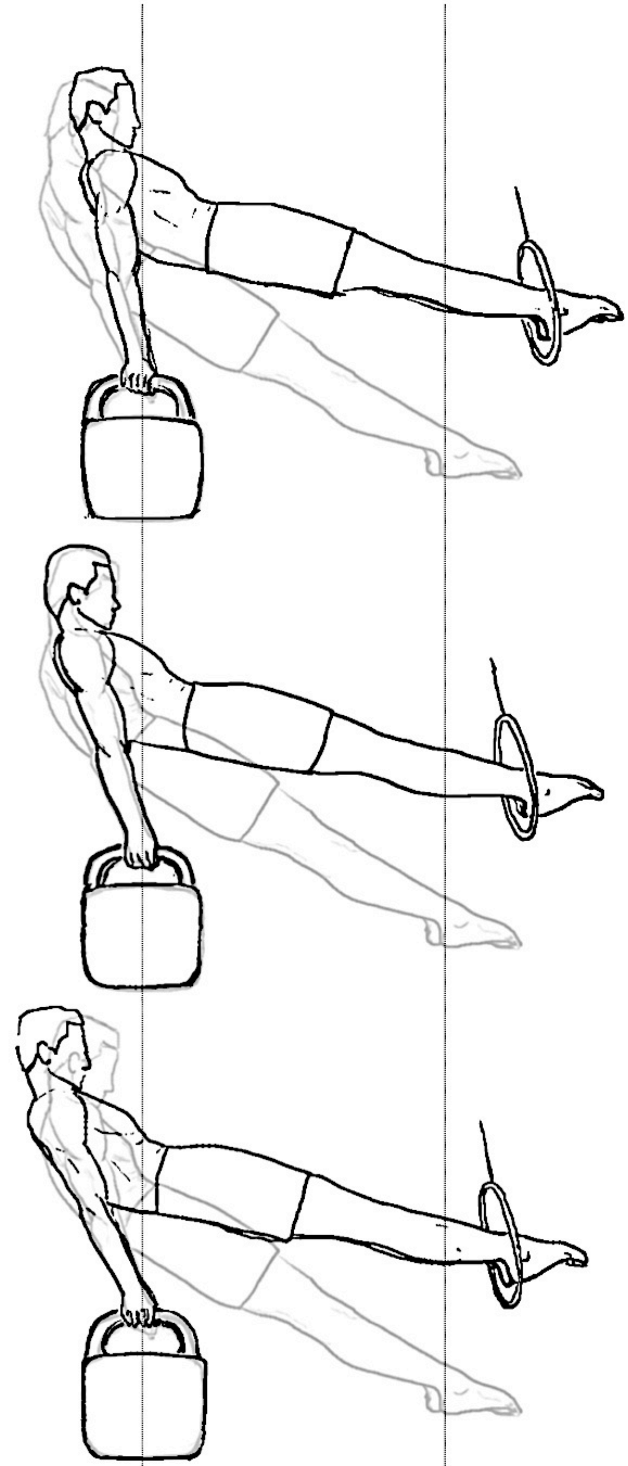

Figure 4-7 Three different body positions with the same body angles. The middle figure shows the average position in this study (the same as the one of Figure 3-6 in chapter three). The top and bottom figures were drawn to visualize more and less arm leaning angle in the same phase. The grey figures were the average positions for circles without the aid (also the same as the one of Figure 3-6 in chapter three). The left vertical line indicates the hand position, and the right vertical line indicates the ankle position for circles without the aid. Compared to the top one, the bottom one would be closer to circles that are dynamically balanced (without the aid) but still achieve the larger amplitude, that is, what gymnasts eventually need to learn.

what gymnasts eventually need to learn. These suggestions might be helpful to reduce the gap between circles with and without the aid. Importantly, these suggestions can be followed in a progressive manner in accordance with a gymnast's improvement. Further research incorporating electromyography and learning evaluation would be beneficial to verify these points.

This kinetic study was subject to all the limitations that were addressed in chapter three. In addition, several special assumptions were necessary to compute the hip joint moments as described in the method section. Therefore, the data must be interpreted within appropriate context.

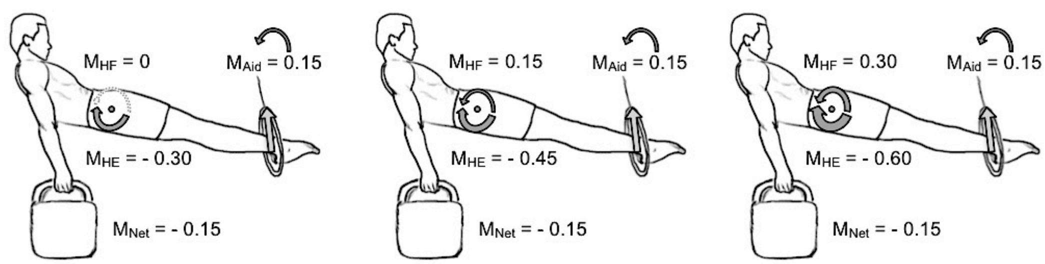

Figure 4-8 Three situations where the net hip joint moments are the same. In this figure, only the hip flexion moment (M_{HF}), the hip extension moment (M_{HE}), and the moment due to the aid reaction force (M_{Aid}) were considered, and all other things are assumed to be identical. The ratio of the magnitude of three moments (M_{HF} : M_{HE} : M_{Aid}) are (0 : 2 : 1) for the left figure, (1 : 3 : 1) for the middle figure, and (2 : 4 : 1) for the right figure. As the co-contraction becomes larger, the relative magnitude of the moment due to the aid reaction force decreases.

4.5 Conclusions

Chapter three and four of this thesis examined the kinematics and kinetics of circles with a suspended aid. The main findings were as follows.

- The aid could function as “spotting” to assist gymnasts in practicing circles with the greater amplitude resulting from a smaller body flexion angle and greater shoulder angles.
- From a mechanical viewpoint, maintaining such a high and large mass-centre rotation during circles was considered impossible or unrealistic without the aid. Whether or not that is desirable depends on the context and focus of training.
- The use of the suspended aid dramatically altered the net moment profiles at the hip joint.
- When a suspended aid is used, it might be advantageous to reduce total duration for a circle, to increase shoulder diameter by increasing arm segment angles with respect to the horizontal plane, and to increase the joint stability at the hip joint by co-contracting extensors and flexors. These points may reduce the gap between circles with and without a suspended aid.

A suspended aid could be used for a variety of purposes, and how to incorporate such training into a learning protocol is left to gymnasts and coaches. However, it is beneficial to know how a suspended aid influences the mechanics of circles. Recognizing its worldwide popularity, we believe that the information provided in this set of studies should be valuable for many practitioners. The next study of this series deals with the question of how circles with a suspended aid would vary depending on the gymnast’s level of expertise.

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Chapter 5

Circles with a Suspended Aid Part IV:
Influence of Expertise

5.1 Introduction

In the previous chapters, circles with the suspended aid were evaluated from different viewpoints. For these studies, the data were based on the gymnasts who could perform circles. The difference in the skill level among the gymnasts was not taken into consideration. Moreover, a suspended aid can be used even for those who are just learning circles. This study focused on how circles with the suspended aid may change depending on the gymnast's level of expertise.

Using a suspended aid can be regarded as being spotted. Spotting can be defined as assistance, by a coach or using a device, for an athlete to complete a task. It can be used for a variety of purposes, and the way of spotting varies depending on the goals of training (Sands, 1996). Importantly, direct spotting allows a coach to adjust the amount of assistance depending on the skill level of the learner, providing a gymnast with gradual progressions. At the first stage of learning, a gymnast may be totally dependent on the spotting. As the gymnast's learning progresses, the coach reduces the amount of spotting. Eventually, the gymnast becomes independent of spotting. This concept is referred to as "progressive spotting" (Kruger, 1976).

The main question here is whether a suspended aid can do progressive spotting. A non-human training aid does not actively do it. However, because the cable tension is dependent on the amount of force that is applied by the gymnast, the aid would play more or less of a role depending on what the gymnast does. Less-skilled gymnasts possibly rely on the aid more than skilled gymnasts do, and consequently, the external force applied from the aid to the gymnast would be more influential for less-skilled gymnasts. In short, the suspended aid may do progressive spotting passively. The possibility of progressive use is regarded as one of the key features for a gymnastics training aid (Rosamond & Yeadon, 2009).

The objective of this paper was to answer such a question, namely, whether or not the characteristics of circles using the suspended aid vary depending on the gymnasts' levels of expertise. We hypothesized that gymnasts become less dependent on the aid as their skill levels improve. As a result, the reaction force from the aid (aid reaction force) would become relatively smaller with respect to the pommel reaction forces, and the kinematic and kinetic difference, due to the use of the aid, would be reduced.

5.2 Methods

This study's experimental set-up and data collection protocol has in large part been described in the chapter three and four. Only the additional methods for the analysis are described here.

5.2.1 Participants

Eighteen gymnasts who participated in the study for chapter three and four were classified into two groups: expert group and intermediate group. From video recordings, four judges with international accreditation scored their circles performed with no aid. Two judges watched the video recorded with camera one, and the other two judges watched the video recorded with camera two. A perfect score was set at 10.0 and a deduction was applied in step of 0.1 according to any technical fault or execution errors. Then, the average of four scores were determined as the final score. The intra-class correlation coefficient, computed as an estimate of the inter-judge reliability, was 0.944. Based on the scores, the top eight gymnasts were selected as expert (the average score = 9.35) and the bottom eight gymnasts consist of the intermediate group (the average score = 8.05).

Additionally, eight more male gymnasts participated in this study. They were capable of performing 20 consecutive circles on a mushroom—a training apparatus that has a circular top surface with no handle—but not on two handles of a pommel horse. This group of eight gymnasts was defined as a developing group. Combined with the expert and intermediate groups, there were three groups of eight gymnasts. A comparison of the gymnasts' physical characteristics and experience are presented in Table 5-1.

All gymnasts had experiences in practicing circles with some form of suspended aids. Written informed consent was obtained of all the gymnasts. Prior to the start of this project, ethical approval was obtained through our institutional research ethics review board.

Table 5-1 Characteristics of each group of the gymnasts (average ± standard deviation).

Items	Experts	Intermediate	Developing
The number of gymnasts	8	8	8
Height (m)	1.63 ± 0.06	1.49 ± 0.11	1.47 ± 0.15
Body mass (kg)	56.0 ± 5.0	42.2 ± 10.2	40.7 ± 12.8
Age (years)	18.1 ± 4.4	14.8 ± 2.1	12.9 ± 2.2
Experience in gymnastics (years)	10.5 ± 2.4	9.3 ± 2.9	4.8 ± 1.3
Training volume (hours/week)	22.7 ± 2.7	19.4 ± 3.4	17.3 ± 1.8
20 Circles on two handles	Able	Able	Unable
Average score	9.35 ± 0.20	8.05 ± 0.72	Not available

5.2.2 Data collection

The developing group performed three sets of 10 circles on the pommel horse only with the suspended aid.

5.2.3 Data analysis

To test the hypothesis, we selected several variables from the previous studies: aid reaction force, pommel reaction force, total duration, shoulder diameter, ankle diameter, body flexion angle, shoulder extension angle during the rear support, and hip joint moments. For aid and pommel reaction forces, only the vertical component was considered. The average resultant force from the two pommels represented the pommel reaction force. The amplitude variables, identified by Baudry et al. (2009), and total duration were selected as discriminative kinematic variables. Based on the hip joint moment profiles during circles with the aid as analysed in chapter four, the average flexion-extension moment was computed for the front and rear support phases, and the average lateral-flexion moment was computed for the entry and exit phases.

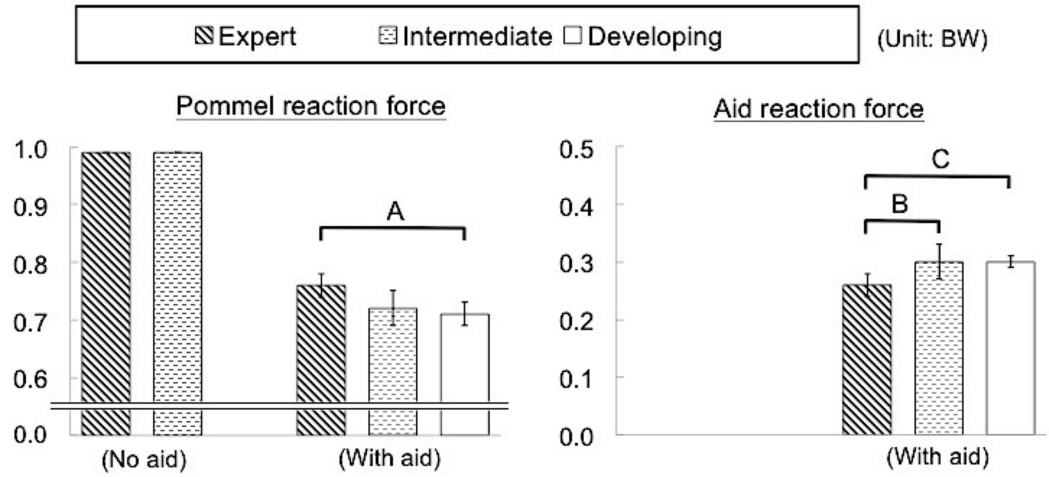
5.2.4 Statistical analysis

Circles with the aid were compared among the three groups, and circles with no aid were compared between the expert and the intermediate groups. No comparison was made between circles with and without the aid. To find the variables that showed practical significance, the dominance statistic (Cliff's *d*, Cliff, 1993), was computed as an effect size measure for each pair-wise comparison. To minimize the number of statistical tests and to maximize statistical power, we selected only eight comparisons, which showed the minimum 0.70 of Cliff's *d*, for the Wilcoxon-Mann-Whitney *U* test. When more than two comparisons within a single variable (e.g. expert vs intermediate and expert vs developing etc.) were over 0.70 of Cliff's *d*, the comparison between the expert and the developing groups was given priority. The experiment-wise error rate was set at $p < 0.0250$, and after the Holm's correction for eight univariate statistical tests, a critical *p* value for each test ranged from 0.0031 to 0.0250 (Knudson, 2009). All statistical significance tests were performed using PASW Statistics 18.0 (SPSS Inc., 2009).

5.3 Results

5.3.1 The pommel and aid reaction forces

During circles with the aid, the expert group showed a greater pommel reaction force and a smaller aid reaction force (Figure 5-1). The average pommel reaction force was approximately 0.99 ± 0.00 BW during circles with no aid for both the expert and intermediate groups. With the aid, it was attenuated to 0.76 ±



Comparisons	Difference	Cliff's *d*	*z*	*p*	Critical *p*
A (0.76 vs 0.71)	0.05	0.97	3.26	0.0011	0.0036
B (0.26 vs 0.30)	0.04	0.78		No test	
C (0.26 vs 0.30)	0.04	1.00	3.36	0.0008	0.0031

Figure 5-1 The comparisons of the external forces on the gymnasts among three groups. The vertical component of the forces was considered. The pommel reaction force is the resultant force of both hands. The comparisons that showed over 0.70 of Cliff's *d* are shown in the bottom table. To minimize the total number of univariate statistical test (Wilcoxon-Mann-Whitney *U* test) in the study, only the comparison between the expert group and developing group was subject to the statistical significance test in case of multiple practical significances within a single variable. The expert group experienced a greater pommel reaction force and a smaller aid reaction force.

0.02 BW (average ± standard deviation) for the expert group, 0.72 ± 0.03 BW for the intermediate group, and 0.71 ± 0.02 BW for the developing group. The developing group supplemented a smaller pommel reaction force with a greater aid reaction force. All gymnasts in the developing group experienced a greater aid reaction force than any gymnast in the expert group. Furthermore, the aid reaction force was largest (0.34 ± 0.02 BW) for the lowest-scored gymnast and smallest for the highest-scored gymnast (0.23 ± 0.01 BW).

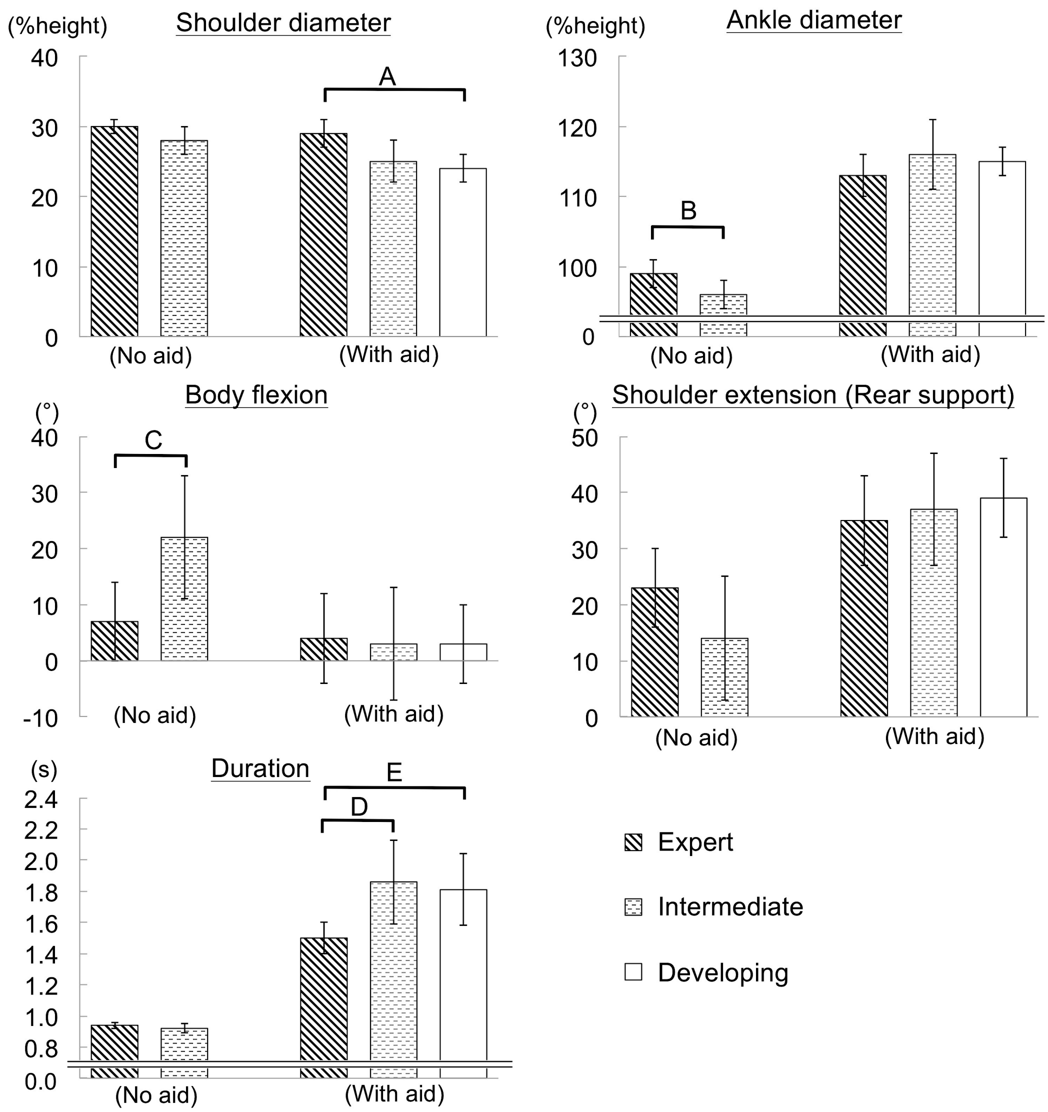
5.3.2 Spatio-temporal characteristics

When circles with no aid were compared between the expert and intermediate groups, significant differences were found in two kinematic variables: ankle diameter and body flexion angle. The expert group showed a larger ankle diameter and a smaller body flexion angle. For the other two amplitude variables, the expert group actually demonstrated larger means, but the differences were not significant because of the small difference relative to the within-group variability.

With the aid, however, the difference between the experts and the other two groups was manifested differently. The expert group had a larger shoulder diameter and a shorter duration during circles with the aid. The difference in the ankle diameter and the body flexion angle became non-significant with the aid.

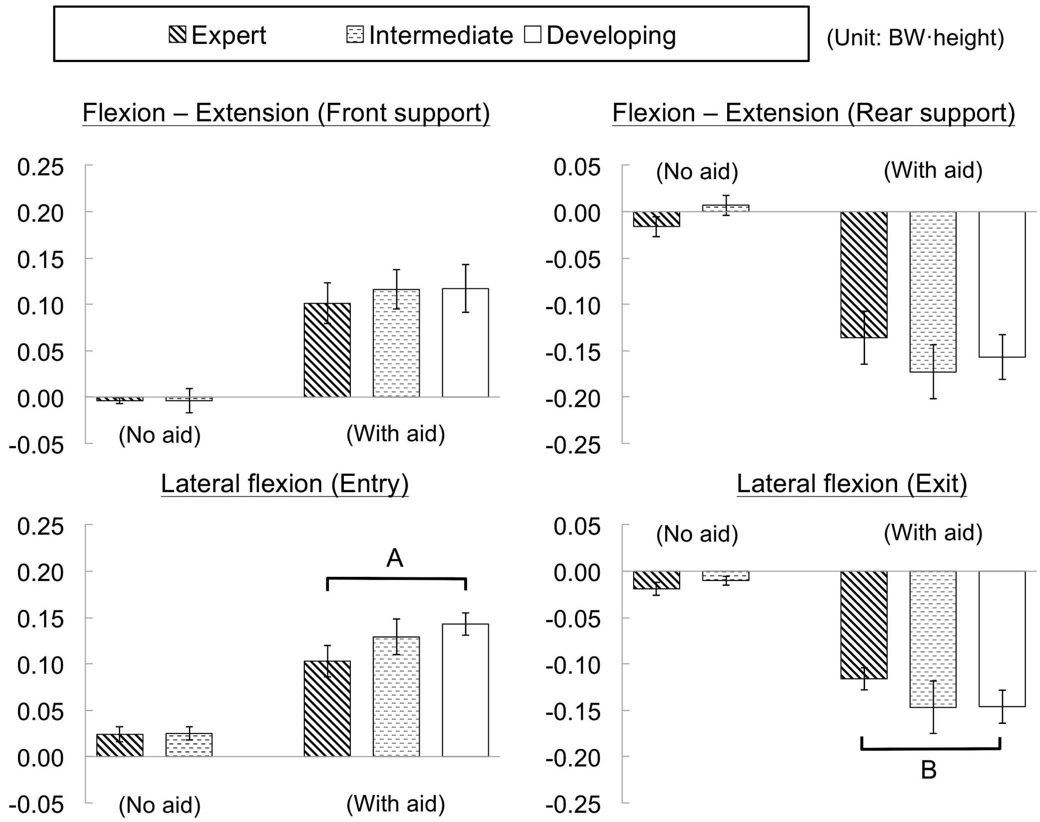
5.3.3 Hip joint moments

Although the expert group had the smallest average values for the net hip joint moments in all phases of the circles with the aid, the practical and statistical significances were found only in the single-support phases. In the entry and exit phases, the expert group showed the smaller leftward-flexion and rightward-flexion moments than the other two groups, respectively. There was no practical significance between the intermediate and developing groups.



Comparisons	Difference	Cliff's *d*	*z*	*p*	Critical *p*
A (29 vs 24)	5	0.81	2.73	0.0064	0.0083
B (99 vs 96)	3	0.88	2.94	0.0032	0.0063
C (7 vs 22)	15	0.78	2.63	0.0086	0.0125
D (1.50 vs 1.86)	0.36	0.78		No test	
E (1.50 vs 1.81)	0.31	0.72	2.42	0.0156	0.0250

Figure 5-2 The comparisons of the representative kinematic variables among the three groups. The comparisons that showed over 0.70 of Cliff's *d* are shown in the bottom table. To minimize the total number of univariate statistical test (Wilcoxon-Mann-Whitney *U* test) in the study, only the comparison between the expert group and developing group was subject to the statistical significance test in case of multiple practical significances within a single variable. The expert group had a larger ankle diameter and a smaller body flexion during circles without the aid. With the aid, the expert group showed a larger shoulder diameter and a shorter duration.



Comparisons	Difference	Cliff's *d*	*z*	*p*	Critical *p*
A (0.10 vs 0.14)	0.04	0.94	3.15	0.0016	0.0042
B (- 0.12 vs – 0.15)	0.03	0.91	3.05	0.0023	0.0050

Figure 5-3 The comparisons of the hip joint moments among the three groups. The comparisons that showed over 0.70 of Cliff's *d* are shown in the bottom table. The mean magnitude of the net hip joint moment was smaller for the expert group in all phases of circles with the aid. In particular, the differences in the single-support phases were practically and statistically significant. For the flexion-extension moment (top), the positive value indicates the flexion moment. For the lateral flexion moment (bottom), the positive value indicates the moment for leftward lateral flexion.

5.4 Discussion

We hypothesized that the gymnast's level of expertise would influence the performance of circles with the aid, and the results of this study supported our hypothesis. The expert gymnasts supported their body weight more with their upper extremities, experiencing a smaller force from the aid. Also, the expert group had a larger shoulder diameter and took a shorter time for a single circle compared to the other two groups. The net hip joint moments were relatively smaller for the expert groups than the intermediate and developing groups.

The amount of aid reaction force was, in a sense, self-selected; the cable tension varies passively depending on how much a gymnast pushes down on the aid. The results showed that the expert group experienced a smaller aid reaction force, suggesting that a more-skilled gymnast does not rely on the aid as much as a less-skilled gymnast does. In this sense, a suspended aid can be used in a progressive manner similar to progressive spotting.

On average, the aid reaction force ranged from 0.23 BW to 0.34 BW even though it was possible for a gymnast to rely on the aid to provide a greater or lesser "spot." No instruction about the performance was given to the gymnasts for this study, so they performed circles with the aid based on personal confidence and comfort level. Interestingly, Threlkeld, Cooper, Monger, Craven, and Haupt (2003) studied gait kinematics with different levels of body weight support, reporting that significant kinematic alteration was induced by 50% and 70% body weight support but not by 30%. According to the data collected by van Hedel and his colleague, hip, knee, and ankle joint trajectories remained almost unchanged during 25% body-weight-supported walking, unlike 50% or 75% body-weight-supported walking (van Hedel, Tomatis, & Müller, 2006). A suspended aid might not be directly compared to a harness for walking because of the different mechanics of the motions and the different point of force application with respect to the main supporting limbs. Nevertheless, these studies imply that over 50% body weight support would cause substantial kinematic alteration. It seems reasonable to conclude that gymnasts feel comfortable in producing the motion of circles with 20-40% body weight supported and that the expert gymnasts were more independent of the aid compared to the other groups.

The results of this study corroborated the suggestions made in the previous chapters. To reduce the gap between circles with and without the aid, it was recommended that the practice of circles with a suspended aid should emphasize a larger shoulder excursion and a shorter total duration. In this study, the expert group showed a significantly greater shoulder diameter and shorter duration during circles with the aid, compared to the other two groups. The experts showed approximately 5° greater incline of the arm segments. This difference in the arm segments' angle for the most part explains the greater shoulder diameter. The slower circles by the intermediate and developing groups may be related to their information-processing capacities (Salmela & Lavoie, 1977) and the smaller pommel reaction forces as discussed in the last two papers.

The influence of using the aid on the amplitude variables was greater for the intermediate group than for the expert group. The expert group demonstrated a significantly greater ankle diameter and a smaller body flexion angle when circles were performed without the aid. These differences between the expert and intermediate groups became non-significant with the aid. The intermediate-group gymnasts demonstrated better body alignment and greater amplitude in the aid-suspended circles compared to their performance without the aid. Thus, the possibility of using a suspended aid for kinematic assistance is further supported although the effect of such training on motor learning is still controversial (Wulf & Shea, 2002).

The smaller hip joint moments for the expert group most likely resulted from a smaller aid reaction force. With the current method, we cannot determine how much co-contraction of the agonists and the antagonists was present during circles. However, as long as the gymnasts experience an aid reaction force around their ankles, external moments relative to the hip joint would be large due to the long moment arm. Suspending a gymnast from a more proximal point would reduce the moment arm of the external force about the hip joint, so it should reduce the magnitude of the external moment given the same aid reaction force. However, changing the point of suspension may influence other kinetic and kinematic characteristics of circles. Studying the consequences of altering the point of suspension on the gymnast may provide practitioners with more information about the use of suspended aids for training and learning.

5.5 Conclusions

The influence of the suspended aid on the kinematics and kinetics of circles depends on a gymnast's level of expertise. When the experts performed circles with the aid, their kinematic behaviour corresponded to what we have suggested to reduce the discrepancy between circles with and without the aid. Also, the experts showed a greater pommel reaction force and a smaller aid reaction force. These results infer less dependency by experts on the aid and the possible use of a suspended aid for progressive spotting.

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Chapter 6

General Discussion and Conclusions

6.1 Summary of each chapter

This series of studies was conducted to answer the question of how a suspended aid influences biomechanical characteristics of circles. In chapter one, the target skill—circles—and practical problems with training circles were introduced. Chapter two concentrated on the effect of using the suspended aid on the pommel reaction forces, confirming that it could reduce the magnitude of the pommel reaction forces during circles while maintaining the general loading pattern. The next study analyzed the kinematics of circles in detail (chapter three). As hypothesized, we found improved amplitude and slower tempo in the circles with the aid. These differences in circle motions were also discussed in terms of the mass-centre kinematics and the reaction forces from the pommels and the aid (chapter four). What is also shown in chapter four was the influence of using the aid on the hip joint moment profiles during circles. In chapter five, we tested the hypothesis that gymnasts become less dependent on the aid as their skill levels improve. The results supported this hypothesis and corroborated the practical suggestions made in the previous chapters regarding training with the aid. In this final chapter, the results from each chapter were put together to propose potential advantages and limitations of training with a suspended aid.

6.2 Potential usage of a suspended aid

Although the ways and purposes of spotting vary depending on the goal of training (Sands, 1996), what a suspended aid does is "kinematic assistance." It can be defined as physical assistance that helps a gymnast experience a skill or a desired motion in the process of learning. This type of spotting is perhaps as common as safety or rescue spotting in gymnastics training. Because many gymnastics movements are far from natural human movement patterns, possible benefits from such experiences would be greater for gymnastics than for other activities that are extension of daily movements such as running, jumping, throwing, and hitting.

The first justification for the usage of kinematic assistance is that gymnasts can actually experience a motion that they eventually want to learn. In chapter three, it was shown that the use of the suspended aid improved the amplitude, one of the most important aspects of circle performance. The significant differences in body flexion and ankle diameter between the expert and intermediate groups became non-significant with the use of the aid (chapter five), suggesting that less-skilled gymnasts could experience a better motion despite their lower skill levels. Chapter three also revealed that the aid increased the shoulder angle, formed by the trunk and the arm segments, throughout a circle. In line with the research by Baudry et al. (2009), the shoulder angle was most discriminative in the rear support phase of all four phases during circles without the aid. Fujihara and Gervais (2010) recognized the possible difficulty in achieving a high rear support position. With the aid, there was no difference in the shoulder angle among three groups (chapter five). It is true that, in a kinetic sense, what gymnasts experience with the aid may be different from what they need to learn, as discussed in chapter four (e.g. joint moment). Nevertheless, it still seems beneficial that there is an opportunity for gymnasts to understand and realize the joint angular positions for a desired motion of circles. According to Seidler (2010), including a variety of learning programs, instead of concentrating on a particular program, may enhance the rate of learning.

Kinematic assistance by the aid can also be used to control physical load on the upper extremities. Although such a usage of a suspended aid may not be very common in the coaching literature, its potential is quite remarkable. First, circles with a suspended aid can be a good progressive stage to develop necessary support strength especially for young gymnasts or beginners (Readhead, 1997). As demonstrated in chapter two, the magnitude of the pommel reaction forces was attenuated in all components by the use of the aid, but the force-loading pattern remained relatively similar. Second, training with less loading can be a valuable option for rehabilitation after upper extremity injuries. Such an application is analogous to a body-weight-support harness for walking rehabilitation after hip joint injuries (Giangregorio et al., 2009). Alternately, it can be used as one way of controlling training volume to reduce the risk of overuse injuries. The motion of circles is so unique that there are not many training variations to experience a similar motion or weight-bearing pattern. Therefore, the possibility to experience a similar loading pattern with a smaller magnitude is certainly a beneficial alternative to no-aid circles for many gymnasts.

In relation to the topic of injury prevention, it should be noted that impulse over each hand contact was increased with the use of the aid. For each hand contact, the xyz-resultant impulse was 0.65 BW·s during circles with the aid, whereas it was 0.49 BW·s without the aid, on average. Even though the average force, the active peak, the impact peak, and the loading rate were all reduced with the use of the aid (chapter two), the longer contact duration contributed to the larger impulse. In fact, an impulse, at least in the context of injury prevention, is not as common as the variables that were analysed in chapter two. However, if the control of training volume is of interest, possible fatigue related to longer muscle activation for each contact should be taken into account. For the same number of circles, the intensity of pommel reaction forces (e.g. peak force and average force) is smaller, but the total duration of weight bearing and the impulse are larger for the circles with the aid.

It was shown in chapter five that the amount of body weight support was somewhat self-selected. The expert group seemed to rely on the aid less than the intermediate and developing groups. Such a progressive usage of the aid is supported by the challenge point hypothesis, which suggests that optimal learning is a function of task difficulty and individual's skill level (Guadagnoli & Lee, 2004). Consider, for example, Marchal-Crespo and Reinkensmeyer's study (2008). They controlled the amount of guidance for a steering task using a computer-programmed algorithm, reporting that the subjects in the "guidance-as-needed" group learned the task better than those in the "fixed-guidance" group. The suspended aid provided "assistance as needed," and it is, in a sense, progressive spotting (Kruger, 1976). However, a suspended aid would not bridge completely from 100%-assistance to 0% assistance. The average amount of support by a suspended aid seems to vary in the range of 20-40% body weight support according to the results of this research.

The value of kinematic assistance may be enhanced when psychological aspects are considered. Nakamura and Shuto (2002) conducted a case study on two gymnasts who experienced difficulty in making the transition from circles on a mushroom to circles on the two handles of a pommel horse. Their research revealed the gymnasts' hesitation in grabbing the right handle behind their bodies and in shifting the body weight over their right arms. In the present study, no kinematical evidence showed that the developing gymnasts hesitated to catch the right handle. A suspended aid might reduce a gymnast's fear of falling due to missing a handle. Also, circles can be difficult enough to discourage a beginner to practice. A suspended aid can reduce the task difficulty, potentially making training safer and more encouraging.

Finally, kinematic assistance can be employed to allow a gymnast to focus on a more specific aspect of the skill by reducing physical and/or psychological demand related to performing the skill. Reinkensmeyer and Patton (2009) argued that guidance could help a learner to concentrate on task components other than the main task. Similarly, with a suspended aid, a gymnast may be able to pay attention to the most important aspect at the progressive stages of learning. Also, allowing gymnasts to perform slow circles should help to simplify the target skill and facilitate learning (Schmidt & Wrisberg, 2008, p.240). Learning complicated skills, like circles, might benefit from reducing the processing demand unlike learning a simple laboratory task (Wulf & Shea, 2002).

6.3 Limitations and suggestions for using a suspended aid

It is unlikely that a single training method alone is perfect especially when a skill is complex. A suspended aid for learning circles is not an exception. Despite many potential uses discussed above, there are some limitations. For a suspended aid to be used effectively, its downside should be understood appropriately and should be compensated with other training variations.

The first possible limitation noticed in this study was the slowness of the circles with the aid. Given the increased moment of inertia and the reduced pommel reaction forces, it would be difficult for gymnasts to perform circles with a suspended aid at the same speed as circles with no aid, even if they were requested to do so (chapters three and four). Being able to perform circles slowly is an advantage, but being unable to perform circles as fast as they should be is definitely a disadvantage of this training method. Although the temporal ratio of each phase of the circles were relatively similar to circles without the aid, absolute temporal rhythm could not be the primary focus of training and should be supplemented with other training. Also, to make a transition from circles with a suspended aid to circles with no aid more easily, it may be a good idea to encourage gymnasts to increase the speed of circles with a suspended aid as they improve their skill level.

At the cost of kinematic assistance by a suspended aid, kinetic alteration appears to be inevitable. In chapter four, the significant differences in the net hip joint moment profiles were found between circles with and without the aid. It was suggested that co-contracting the agonists and antagonists would reduce the relative influence of the aid reaction force on the moment equation. However, net hip joint moments during circles with a suspended aid will always be different from those during circles with no aid. This limitation is particularly important to be understood because correcting body segment alignment is often regarded as one of the main goals for training with a suspended aid (Karácsony & Čuk, 1998; Yoshida & Shiroma, 2001).

More obvious influence is the dynamic balance required for performing the skill. During circles with no aid, the mass centre does not pass over the base of support. On the other hand, a suspended aid provides another fulcrum at the distal end of the legs, making the base of support so large that the mass centre can stay above that. That is, with the aid, circles can be even stopped without falling. Without a suspended aid, however, the motion of mass centre needs to be dynamically balanced throughout a circle. The ability to maintain the dynamic balance necessary for performing circles would not be learned by training with a suspended aid. Nevertheless, as suggested in chapter four and five, a larger horizontal excursion of the shoulders in accordance with a larger ankle excursion might reduce the dependence on the aid. Such a motion corresponds to the experts' behaviour for circles (chapter five) and would encourage gymnasts to learn a desired body position.

Lastly, we should be cautious about the benefit derived from kinematic assistance. Multiple studies in motor learning have shown that robotic guidance is not advantageous for learning a desired trajectory (Liu, Cramer, & Reinkensmeyer, 2006; O'Malley, Gupta, Gen, & Yanfang, 2006) or may produce even detrimental effects (Tsutsui & Imanaka, 2003; Winstein, Pohl, & Lewthwaite, 1994), when compared to no guidance. The term "assistance," instead of "guidance," was selected as a function of a suspended aid because it does not actually "guide" a motion. Regardless of which term is used here, a lot of evidence has suggested that a mere kinematic imitation does not seem to allow the motor system to translate such an experience into a desired motor command. One possible explanation for this is that the kinetics of the movement (e.g. muscle force production) performed with kinematic guidance can be different from the kinetics that need to be learned (Reinkensmeyer & Patton, 2009). Importantly, many motor-learning studies employ a simple laboratory task. For learning complicated tasks, the influence of kinematic assistance is more controversial. Wulf and Shea (2002) asserted that the results based on simple laboratory tasks could not be generalized to motor learning on more complicated tasks. In fact, there is a study that showed positive learning effects of assistance on slalom-type movement on a ski simulator (Wulf & Toole, 1999). Assessing the training with a suspended aid from a motor learning perspective will certainly be an intriguing next step.

6.4 Knee-suspended trials

6.4.1 What was planned

According to the previous chapters, using the suspended aid influences kinematics and kinetics of circles while reducing the wrist load. Some changes due to the use of the aid can be an intention of training, but other changes may not. For example, the force attenuation on the wrists can be a useful option for a variety of training purposes, but the alteration of net hip joint moments could delay or hinder the transition from circles with the aid to without. In chapter four, it was discussed that the length of moment arm relative to the hip joints might influence the magnitude of the external moment caused by the external force. This discussion led us to ask what if a gymnast is suspended in a different way. In such a method, we wonder how the mechanical alterations would be different from those seen in the traditional method. The last paper of the series was planned to test a different use of the aid and to extend the possibility of this training method.

Using our aid, it was possible to suspend a gymnast from his knees instead of his ankles without any modification. By attaching the aid about the knees, the moment arm of the external force about the hip joint would be significantly reduced comparing to the traditional usage of the aid (Figure 6-1). The aim of this

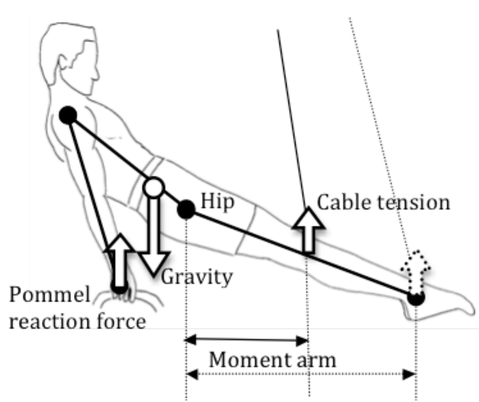

Figure 6-1 A shorter moment arm for the cable tension when the suspended aid is attached to the knees instead of the ankles.

study was to investigate whether or not suspending the body from the knees, instead of the ankles, reduces the undesirable alteration of circles mechanics due to the use of the aid while keeping the same level of stress reduction from the upper extremities. A similar amount of stress reduction on the upper extremities was expected, but the change in the kinematic and kinetic characteristics of circles might be significant.

6.4.2 Problems encountered in the data collection

Based on several pilot experiments with a single subject, we expected that gymnasts who can perform circles with the aid in the traditional way (i.e. ankle suspended) would be able to perform circles with the aid fixed around their knees. We planned to have all gymnasts perform circles with the aid around their knees as well as circles with the aid around their ankles. However, we encountered some problems with collecting the data for the knee-suspended trials.

The first problem was related to fixing the aid to the legs. Although the aid reaction force was predominantly composed of the vertical component, the horizontal component still existed as a result of the difference between the centrifugal force for the aid and the horizontal component of the cable tension. For the ankle-suspended trials, the peak value of the normal component of the aid reaction force was approximately 0.10 BW on average. This force was large enough to move the aid along the legs, if the aid was not fixed to the legs. We had no problem with tying the legs up to the aid around the ankles. For the knee trials, however, it was difficult to simultaneously achieve enough tightness of the bungee cord to keep the legs in the centre of the aid and enough looseness to let the legs go through up to the knee position, especially with the cluster markers on the shanks. The larger circumference of the legs around the knees made tying even more difficult than for the ankles. Moreover, the first two subjects were taller but not as skilled as the gymnast for the pilot study. Consequently, getting these gymnasts ready for knee-suspended trials was much more challenging and time consuming than expected. Then, when the aid was not well tied up, it moved along the legs, removing or breaking the cluster markers on the thigh segments. These unforeseen outcomes required that the markers be replaced and that the anatomical calibration be repeated.

The second problem was that a knee-suspended trial seemed unexpectedly more difficult than (or different from) an ankle-suspended trial. In the pilot study, the gymnast did not have any problem with performing circles with the aid around his knees. However, the first two subjects needed substantially more time for practicing the knee-suspended circles than the ankle-suspended circles. Together with the difficulty in tying up the aid, even the best-scored gymnast presented some problems with performing circles with the aid around his knees and chose more than five practices to acclimate to this different configuration.

After we encountered these problems with the best gymnast, we decided not to ask all subjects to perform knee-suspended circles for two reasons. First, the difficulty in collecting the data for the knee-suspended condition would negatively influence all data collection for the other conditions. Second, even if the data were obtained for the knee-suspended condition, the effects of practice would overly influence the results. Hence, we believed that it was not ethically or ecologically reasonable to request all participants to perform circles with a knee-suspended condition.

Nevertheless, we successfully collected the data for the knee-suspended trials with a single gymnast in a pilot experiment. This gymnast had experience in practicing circles with the aid around his knees, and he did not show any difficulty in performing the knee-suspended trials. His data were presented in the appendix B as exploratory single-case study for future research.

6.5 Conclusions

A suspended aid has been used at least over 30 years (Russell & Herb, 1978). There has been a lot of anecdotal support and criticism for practicing circles with a suspended aid, but little, if any, empirical evidence has supported or refuted its use. The present work provided biomechanical evidence showing the attenuated pommel reaction forces, the increased circle amplitude, and the altered hip joint moment profiles and temporal rhythm during circles with the aid. It was also found that the experts were less dependent on the aid. Based on these results, a variety of potential uses and the limitations were discussed, and we believe that coaches and gymnasts will benefit from the information provided in this dissertation for developing their optimal training protocols. Our conclusion is that a suspended aid is a useful training option when kinematic assistance is likely to be beneficial for achieving the intended goal of training.

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Appendix A

Rationale for the Methodology in the Proposal

A.1 Research design, statistical significance tests, and sample size

The research design was determined based on the feasibility of conducting statistical significance tests. To investigate the influence of using the aid, circles need to be performed in three conditions: circles with no aid, circles with the aid around the ankles, and circles with the aid around the knees [A-1].

No aid	With the aid (ankle)	With the aid (knee)

To investigate the influence of gymnasts' level on the performance, at least two or possibly three levels of gymnasts were needed.

Expert	Intermediate	Developing

To investigate everything collectively, the design would be 3 x 3 as shown below.

	No aid	Aid (ankle)	Aid (knee)
Expert	✓	✓	✓
Intermediate	✓	✓	✓
Developing	✓	✓	✓

Another option was to use only two levels of groups for gymnasts.

	No aid	Aid (ankle)	Aid (knee)
Expert	✓	✓	✓
Developing	✓	✓	✓

[A-1] The knee-suspended trials were not asked for all subjects due to the problems described in chapter six (pp. 116-118).

In either case, gymnasts who cannot perform circles without the aid should be included in the design, and they were classified into the developing group. That is, the design could not be a complete factorial design.

	No aid	Aid (ankle)	Aid (knee)
Expert	✓	✓	✓
Intermediate	✓	✓	✓
Developing	NA	✓	✓

Or

	No aid	Aid (ankle)	Aid (knee)
Expert	✓	✓	✓
Developing	NA	✓	✓

In fact, a number of methods to analyse an incomplete design are known, such as Latin-Square design and fractional-factorial designs. These designs can effectively identify main effects with fewer subjects, but any interaction has to be negligible, which is not the case. To avoid an incomplete design, the design could be split into two complete designs as follows.

	No aid	Aid (ankle)	Aid (knee)
Expert	✓	✓	✓
Intermediate	✓	✓	✓

And

	Aid (ankle)	Aid (knee)
Expert	✓	✓
Intermediate	✓	✓
Developing	✓	✓

Or

	No aid	Aid (ankle)	Aid (knee)
Expert	✓	✓	✓

And

	Aid (ankle)	Aid (knee)
Expert	✓	✓
Developing	✓	✓

Although these designs involve redundant information, incompleteness due to the empty cell can be solved.

Another important factor was the availability of gymnasts. In general, parametric tests are preferred to non-parametric tests because of the greater statistical power. In health and sport sciences, however, it is often difficult to find or recruit enough subjects to ensure that the normality assumption for parametric tests can be met just depending on the central limit theorem. This research was not an exception. The minimum numbers of gymnasts for the above designs to expect normality in the data, according to Tabachnick & Fidell's procedure (Tabachnick & Fidell, 2007), are 22 (2x3 mixed ANOVA), 24 (3x2 mixed ANOVA), 11 (1x3 repeated-measures ANOVA), and 22 (2x2 mixed ANOVA), respectively. Unfortunately, no more than 14 gymnasts (within 250 km) could perform circles on the pommel horse and at most half of them could be considered as elite gymnasts [A-2]. With such a small number of samples, the central limit theorem cannot guarantee the normality of data.

[A-2] Fortunately, more gymnasts could take part in the study. The additional gymnasts were the participants of the national training camp held at the local gymnastics club during the data collection period.

Even when a sample size is not large enough to automatically assume the normality of data, parametric tests may still be used if the normality of data is checked with a formal test (e.g. Kolmogorov-Smirnov test or Shapiro-Wilk test). Depending on the results of a normality test, either parametric or nonparametric test can be used. When nonparametric alternatives are available for a design, such a practice could be acceptable. The problem here is that nonparametric alternatives are not generally available for a factorial design. It is true that several nonparametric procedures for nonparametric data have been developed (See Shah & Madden, 2004; Brunner & Puri, 2001), no statistical software has incorporated such novel techniques. As a result, extensive knowledge about advanced statistics and programming in statistical software is required.

When a small number of samples are available, it may be better to plan to use nonparametric tests from the beginning rather than relying on the results of a normality test. Some authors recommend the use of nonparametric tests because the loss of statistical power compared to parametric counterparts is actually very small even when the data are suitable for parametric tests (Kitchen, 2009; Tomkins, 2006). To use nonparametric statistics, factorial design should be avoided for the reason discussed above. Therefore, the design was modified as follows.

Design 1

	No aid	Aid (ankle)
Expert + intermediate	✓	✓

Design 2

	Aid (ankle)
Expert	✓
Intermediate	✓
Developing	✓

Design 3

	Aid (ankle)	Aid (knee)
Expert	✓	✓

	Aid (ankle)	Aid (knee)
Intermediate	✓	✓

	Aid (ankle)	Aid (knee)
Developing	✓	✓

Design 1 focused only on the difference between circles with no aid and circles with the aid around the ankles, which was the traditional use of the aid. This design was used for part one, two, and three of the series, comparing these two conditions from a different perspective. Part four of the series used design 2 to investigate the influence of the gymnasts' level of expertise on the usage of the aid. Then, assuming that there were differences in the usage of the aid among the different levels of gymnasts, part five of the series was supposed to use design 3 although the knee-suspended trials were removed from the part of the study due to the problems encountered during the data collection (see chapter 6).

Nonparametric tests were available for these simple designs. Designs 1 and 3 could be analysed using the Wilcoxon signed rank test, and design 2 can be analysed using the Kruskal-Wallis *H* test or the Wilcoxon-Mann-Whitney *U* test for each pair-wise comparison. To maximize the statistical power, the number of participants was maximized. The estimated maximal number of gymnasts in the expert group was seven. For the sake of simplicity of the analysis and the interpretation of the results, the design should be balanced. That is, all groups should have the same number of gymnasts. Therefore, we planned to recruit seven gymnasts in each group (total = 21) for this study [A-3].

A statistical power analysis is not common for a nonparametric test because the knowledge about the distribution, which is often not available, is required for such an analysis. According to Simon (2008), the sample size for the Wilcoxon signed rank test would require 1.157 times more than a repeated – measures *t*-test to achieve the same level of statistical power. Thus, a necessary effect size to obtain the statistical power of 0.80 was computed using G*Power 3 (Faul, Erdfelder, Lang, & Buchner, 2007) with the condition of a two-tailed *t*-test, the sample size = 6 (6 x 1.157 = 6.942 < 7 = the sample size for this study), and the alpha value = 0.025, resulting in Cohen's $d = 1.71$. Likewise, the sample size for the Kruskal-Wallis *H* test would require 1.157 times more than a one-way randomized-group ANOVA for the same level of statistical power. A necessary effect size to obtain the statistical power of 0.80 was computed using G*Power 3 (Faul et al., 2007) with the condition of a one-way randomized-group ANOVA, the sample size = 18 (18 x 1.157 = 20.826 < 21 = the sample size for this study), and the alpha value = 0.025, resulting in partial $\eta^2 = 0.455$. Both Cohen's *d* and the partial η^2 are effect sizes for parametric data, so the computations are only estimations to obtain a rough idea about the statistical power in this study.

[A-3] See the footnote A-2 on page 124.

Nevertheless, it seemed that the statistical power of 0.80 could be achieved with reasonable effect sizes.

A.2 Trial size and the number of circles to be performed

Averaging data based on multiple trials is common in biomechanics to obtain more representative data of the athlete's technique. Mullineaux, Bartlett, and Bennett (2001) emphasized the importance of multiple trials for human performance analysis to increase the reliability of data and subsequently statistical power. Although no simple method to determine required trial size has been fully explored, Mullineaux et al. (2001) recommended to use the average of at least three trials to balance between practicality and statistical issues. By following their recommendation, the number of sets for each condition in this study was determined to be three.

However, circles are cyclic in nature; therefore, multiple-circles data can be obtained with a single trial without imposing excessive physical or mental stresses on the participants. To determine how many circles should be used for the research, a small pilot analysis was performed using the data collected for my master's thesis. The data of vertical pommel reaction force was averaged over different number of circles. The average of 30 circles was used as the criterion, and the per cent root mean square difference (%RMSD) from the criterion was computed over different number of circles to be averaged. Figure A-1 depicts how the deviation from the criteria decreases as the number of circles to be averaged increases. The %RMSD quickly decreases up to the point where 6 circles are to be

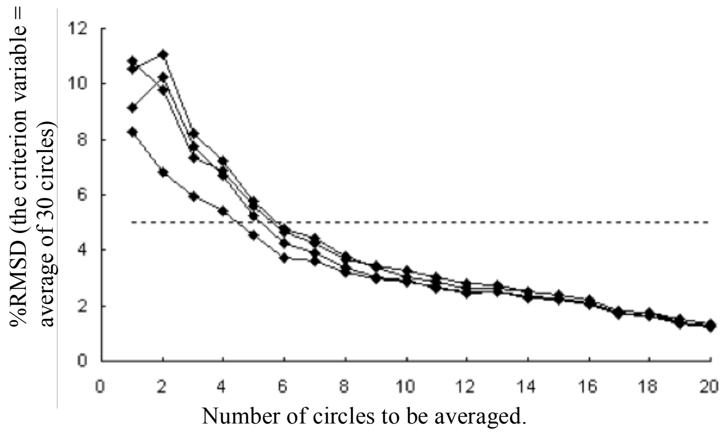

Figure A-1 Relationship between %RMSD from the average of 30 circles and the number of circles to be averaged.

averaged. Also, at the same points, all 4 gymnasts, who were randomly selected out of 17 participants, showed less than 5%RMSD. This means that the deviation from the average of 30 circles is less than 5% if more than 6 circles are averaged.

In the recent research on circles, 10 circles were commonly used as a single trial. (Baudry, Leroy, & Chollet., 2003; Baudry, Leroy, Thouvarecq, & Choller. 2006; Baudry, Seifert, & Leroy, 2008; Baudry et al. 2009; Fujihara & Gervais, 2010; Grassi et al., 2005). In fact, the age-grouped gymnasts in Canada are used to performing 10 circles because of the compulsory routines (Gymnastics Canada, 2008). Thus, the number of circles was determined as 10 for each trial. The first two circles and the last circle were not used as mounting and dismounting transitions. The average of seven circles was used as representative of gymnast's each trial.

In summary, gymnasts performed three sets of 10 circles for each condition. The expert group and the intermediate group had two conditions (60 circles), and the developing group had one condition (30 circles). The total number of circles for these trials and warming-ups are much less than their usual training volume. The fatigue factor was minimized by ensuring enough rest between trials.

A.3 Accuracy test

Motion capture systems or computer software usually report information about the accuracy during calibration or 3-D kinematic reconstruction. It is better, however, to assess the accuracy of the measurement independently of the calibration procedures. The accuracy of the calibration should be tested. For this purpose, there are two main procedures. One is a marker displacement measurement, and the other is an inter-marker distance measurement (Chiari, Croce, Leardini, & Cappozzo, 2005).

For a marker displacement measurement, a marker is moved in the measurement volume through a known trajectory. Then, the reconstructed marker trajectories are compared to the known trajectories. This type of tests usually requires a special device to move a marker over a known spatial trajectory. Hence, an inter-marker distance method may be more practical.

Typically, an inter-marker distance measurement involves the static or dynamic recording of a rigid bar carrying at least two markers placed at a known distance. The inter-marker distance is computed based on the reconstructed trajectories of the markers and compared to the known distance. There are some advanced procedures for an inter-marker distance measurement by combining the use of a force plate (e.g. Holden, Selbie, & Stanhope, 2003; Lewis, Stewart, Postans, & Trevelyan, 2007). Such procedures would be useful to assess the validity of data when the accuracy of information about the centre of pressure is critical. In the current study, however, the location of the centre of pressure was not of interest. A simple inter-marker distance measurement was sufficient for assessing the accuracy of kinematic reconstruction. A calibration wand was probably the most appropriate tool for a test because the distance between two markers is accurately known. Accuracy tests were performed by moving the wand throughout the entire measurement volume as conducted by Cappozzo and his colleague (Cappozzo et al., 1993).

The range and the standard deviation of the wand can be possible assessments of the accuracy of the measurement. In addition, the mean difference between the measured and the true distance as well as its 95% confidence interval might be useful for assessing the reliability of measurements (chapter 3, pp. 48-49).

A.4 Sampling rate

The sampling rate for force data commonly ranges between 500 Hz and 2000 Hz. Markolf, Shapiro, Mandelbaum, and Teurlings (1990) sampled the force data on a pommel at 200 Hz, but they additionally record the data sampled at 2000 Hz to analyse loading rate for the impact phases. Woodard and his colleagues used the data sampled at 500 Hz to compare several computational methods for loading rate (Woodard, James & Messier, 1999). According to Lees and Lake (2008), a sampling rate of 1000 Hz is common for force data. We recorded force data at 1000 Hz for our previous study (Fujihara, Fuchimoto, & Gervais, 2009).

The motion of circles can be captured well without a high-speed camera. In general, circles are videotaped at 50 Hz or 60 Hz, depending on the video standard in the region where the study is conducted. To capture hand-contact and hand-release positions, however, it may be better to capture the motion at a higher sampling frequency if possible. Qualisys system with MCU 240 cameras allows us to set any sampling rate between 1 Hz and 240 Hz.

In this study, kinematic data, force data from two force plates, and force data from the load cell should be synchronized. Qualisys Track Manager has a function to record analog signals while tracking markers. Using a 16-channel analog board, all force data can be simultaneously recorded with kinematic data. The system allowed us to set a sampling rate for the analog signal as the number of data samples per frame. This automatically guaranteed Lipfert and his colleague's recommendation that the sampling frequency of a device should be set at a simple multiple of that of another device to reduce error (Lipfert, Günther, & Seyfarth, 2009).

Taken together, we decided to record kinematic data at 100 Hz and force data at 1000 Hz (10 data samples per frame). It was possible to sample at a twice higher rate, namely, 200 Hz and 2000 Hz, but nothing would be gained when analysing motions like circles with such a high sampling frequency.

A.5 Body segment parameters

Using subject-specific inertia parameters would produce the most accurate results, but there is always a trade-off between the required accuracy and the amount of time and effort for extensive anthropometric measurements. For example, the model developed by Hatze (1980) requires 242 anthropometric measurements, and several hours of measurements are required. Taking such a long time for detailed measurements may not be worth doing for the purpose of this study. The model developed by Yeadon (1990) requires 95 anthropometric measurements. Yeadon's model requires less time of measurement than Hatze's model—30 minutes according to the author. However, this model was developed for an aerial movement. The assumption that the neck and wrists do not move would result in decreased accuracy when the model is applied to a gymnast doing circles.

Regression models are often more convenient, requiring fewer measurements. Yeadon and Morlock (1989) developed a non-linear regression model based on the data obtained by Chandler, Clauser, McConville, Reynolds, and Young (1975). Although relying on Chandler et al.'s data could limit its application due to the restricted number of samples, Jensen and Fletcher (1993) extended the use of their regression equations by proposing a different set of coefficients developed based on 7 male and 12 female living subjects. However, Yeadon and Morlock's regression equations are only for estimation of moments of inertia. When segmental mass centres need to be determined as in the current study, a different set of parameters, such as Dempster (1955) would be required.

Moreover, it is inappropriate to apply the regression equations based on elderly subjects for the young gymnasts who participated in this study.

Zatsiorsky and his colleagues proposed several sets of regression model (Zatsiorsky & Seluyanov, 1983; 1985; Zatsiorsky, Seluyanov, & Chugunova, 1990a; 1990b). All of them are based on 100 young male Caucasian with the average height of 174.1 cm (SD = 6.2) and the average weight of 73.0 kg (SD = 9.1). These body sizes may be larger than the participants for the current study, but their data set is definitely one of the best parameter sets available. The largest problem is that the anatomical landmarks for their data set are not convenient.

The best compromise for this study was de Leva's data set (de Leva, 1996). He modified Zatsiorsky and Seluyanov's data using different anatomical landmarks. Although only the average data is available, the use of joint centres as reference points is very convenient for the kinematic and kinetic analysis of human motion. In addition, the participants were not required to undergo extensive anthropometric measurement. Using the same parameters as our previous studies (Fujihara et al., 2009; Fujihara & Gervais, 2010) also allowed us to make comparisons between the studies. It should be noted that some of the gymnasts in this study were children who did not fit well to the characteristics of Zatsiorsky and Seluyanov's samples. Jensen (1986 & 1989) reported body segment parameters for Caucasian children, but unfortunately, the data can be used only for two-dimensional analysis. In conclusion, the use of de Leva's suggested parameters was the most practical and suitable for the purpose of the study. Any related error was considered to be a limitation of the current work.

A.6 External markers (placement, positions, cluster, soft tissue artefact)

The marker placement was determined to estimate anatomical landmarks for de Leva's suggested parameters. To estimate joint centres, two markers were placed on the surface of each joint. Anatomical landmarks for a trunk, such as suprasternale and xiphion, were also estimated as the middle point of two surface markers. Fujihara and Gervais (2010) used this same approach to conduct their kinematic analysis of circles.

However, the current study had two different aspects from the previous study (Fujihara & Gervais, 2010). First, hip joint centres were estimated using Halborsen's algorithm (2003), whereas Fujihara and Gervais (2010) simply estimated them as the middle points of two surface markers. The positions of hip joint centres could largely influence hip joint angles and hip joint moments. Thus, it was desirable to estimate them as accurate as possible. Although traditional predictive methods (e.g. Davis, Ounpuu, Tyburski, & Gage, 1991) have been widely used, functional methods, in which hip joint centre is usually estimated as the centre of thigh-segment rotation in the pelvis-fixed reference system, has been recommended (Wu et al., 2002). Among available functional methods, a quartic best sphere fitting method presented by Halvorsen (2003) was selected for this study because Cereatti, Donati, Camomilla, Margheritini, and Cappozzo (2009) and Macwilliams (2008) reported its superiority to other methods.

Second difference from the previous study was the use of cluster marker sets for the lower extremities. It was difficult to place and track markers placed on the ankle and knee joints for this study due to the use of the suspended aid. By using cluster marker sets, the markers placed on lower extremities could be removed during trials. Also, using semi-rigid fixtures for clusters would produce better results than placing markers directly on the anatomical landmarks by reducing the effect of soft tissue artefact (Leardini, Chiari, Croce, & Cappozzo, 2005).

Minimizing the error related to soft tissue artefact is important because it is more serious than any instrumental error (Leardini et al., 2005). The soft tissue artefact is usually task dependent and reproducible within subjects. Based on these characteristics, several compensation methods have been introduced. For instance, a multiple calibration method uses two calibrations at two maximal joint positions and linear interpolation for between these points (Cappello, Cappozzo, La Palombara, Lucchentti, & Leardini, 1997; Cappello, Stagni, Fantozzi, & Leardini, 2005). In a dynamic calibration method, anatomical landmark positions are estimated based on joint angles in a motor task (Lucchetti, Cappozzo, Cappello, & Croce, 1998). However, these advanced methods were developed with a simple task, such as sit-to-stand motion. It would be difficult to perform these advanced calibrations for a more complex task like circles. Therefore, the traditional least-square method (Cappello, Cappozzo, Croce, & Leardini, 1997; Cappozzo & Cappello, 1997; Challis, 1995; Söderkvist & Wedin, 1993) was the best available way for this study.

A.7 Smoothing technique and the cut-off frequency

Smoothing technique can be classified into two types. The conventional smoothing methods use a single cut-off frequency to smooth the whole data, while advanced smoothing methods use variable cut-off frequencies as the frequency characteristics of data changes in time. Advanced smoothing methods are beneficial to smooth non-stationary data, which often includes dramatic changes in frequency characteristics, such as a motion with an intense impact. As a compromise, however, the applications of advanced smoothing methods are more complicated than those of conventional methods. In fact, Georgakis, Stergioulas, and Giakas (2002) agreed that signals with low-impact do not require such time-frequency filtering.

Circles involve impacts between the hands and the pommels, but the data of the upper extremities were used only for the computation of the mass centre. Because of the relatively small mass of the upper extremities, the choice of smoothing technique would not largely affect the computation of the mass centre. The data of the lower extremities were more critical for this study since these data were extended to the computation of hip joint moments. During circles, the lower extremities experience no impact. No dramatic change in frequency characteristics for these data was expected. Therefore, the use of conventional smoothing technique was appropriate for this research.

The Butterworth digital filter is one of the most common smoothing techniques in biomechanics. Several methods for determination of the optimal cut-off frequency have been introduced. The residual analysis (Wells & Winter, 1980) has been widely used although it is known that the analysis tends to underestimate the optimal cut-off frequency (Giakaas & Baltzopoulos, 1997; Nagano, Komura, Himeno, & Fukashiro, 2003; Yu, Gabriel, Noble, & An, 1999). As Yu et al. (1999) pointed out, the residual analysis inevitably involves a subjective judgment in terms of the way to draw a regression line. Yokoi and McNitt-Gray (1990) modified the residual analysis, introducing a complete automatic procedure. This method was preferable to the original residual analysis because of its objectivity. The pilot studies showed that the optimal cut-off frequencies determined by Yokoi and McNitt-Gray (1990)'s algorithm are moderately correlated with those determined by the residual analysis. The regression model (Yu et al., 1999) and the autocorrelation-based procedure (Challis, 1999) were also developed for the determination of the optimal cut-off frequency for the Butterworth digital filter. However, they are not as common as the residual analysis.

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Appendix B

Results of Suspended-knee Trials

B.1 Data collection and analysis

A gymnast performed three sets of 10 circles in each of three conditions: with the aid around the ankles, with the aid around the knees, and without the aid. All other details about the data collection procedure were described in the previous chapters. The same variables as chapter five were analysed. For each condition, twenty-one circles were averaged as done for the main chapters of this study.

B.2 Results and Discussion

Although the external validity was limited, the results were supportive for our hypotheses. The magnitude of the force attenuation by the use of the aid was very similar between the ankle- and knee-suspended conditions, but the kinematic and kinetic alterations were more moderate in the knee-suspended conditions.

In terms of the discriminative kinematic variables, compared to the ankle-suspended circles, the knee-suspended circles were generally more similar to no-aid circles. The ankle diameter was also increased in both ankle- and knee-suspended trials. However, the knee-suspended circles showed smaller ankle diameter than the ankle-suspended circles. Similarly, the use of the aid reduced

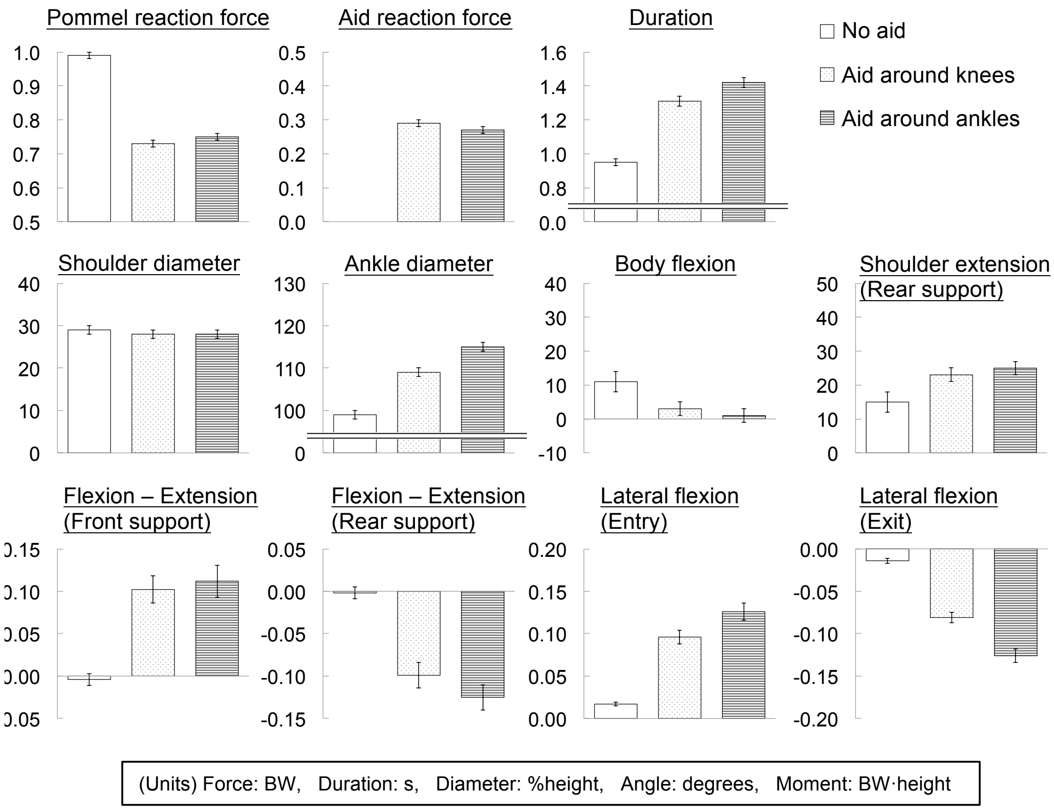

Figure B-1 The comparison of discriminative variables among circles with no aid, circles with the aid around the ankles, and circles with the aid around the knees. The data for each condition is based on the average of 21 circles by a single subject.

the body flexion and increased the shoulder extension in both knee- and ankle-suspended conditions, but the difference from the no-aid trials was slightly smaller for the knee-suspended condition. The shoulder diameter was very similar among three conditions. In other words, the aid assisted the gymnast in improving the amplitude of circles regardless of the point of suspension, but the knee-suspended circles were slightly closer to the no-aid circles than the ankle-suspended circles were.

There are two possible explanations for this. During circles with no aid, the knees generally have less vertical motions than the ankles. For this subject, the range of vertical motion of the knee centre was approximately 0.24 m for the ankle centre and 0.12 m for the knee centre. Because the cable that suspended the aid was non-elastic, the vertical motion of the suspended part of the legs was strongly constrained. The influence of this constraint was more significant for the ankle-suspended condition because of its greater potential of the vertical motions. Second explanation is that the height of the aid kept the ankles at very high positions during the ankle-suspended trials. The aid was set as low as possible without contacting the pommel horse. However, the ankles were positioned in the centre of the aid, so it was approximately 0.2 m higher than the pommel horse. In the knee-suspended conditions, on the other hand, the ankles could go lower, resulting in a more similar motion to no-aid circles.

The duration for a knee-suspended circle was approximately 0.1 seconds shorter than that for an ankle-suspended circle. This difference could be primarily attributed to the decrease in the moment of inertia due to the aid. As discussed in chapter three, having the aid at the distal part of the body would increase the moment of inertia of the body. In the knee-suspended condition, this additional mass was closer to the mass centre of the body, resulting in the smaller moment of inertia for the same mass increment. Although the speed of circles was still based on the individual's comfort in both the knee- and ankle-suspended trials, the influence of the greater moment of inertia was decreased in the knee-suspended circles.

As hypothesized, suspending the legs from the knee region reduced the alteration of the net hip joint moment. This was most likely achieved by the decrease in the length of the moment arm for the aid reaction force relative to the hip joints. In the front support, however, there was no practically significant difference in the net hip joint moment between the knee- and ankle-suspended trials. In this phase, the mean aid reaction force was actually greater for the knee-suspended circles than for the ankle-suspended circles (0.27 BW vs 0.21 BW), whereas the differences in the other phases were smaller than 0.02 BW. It seemed that the difference in the length of the moment arm was compensated with the difference in the magnitude of the aid reaction force, causing a similar amount of the external moment on the leg segment. These results confirmed that the point of suspension largely, but not solely, influences the changes in the net hip joint moment profiles during the circles with a suspended aid.

B.3 Conclusions

The results implied the potentials for suspending a body from a point that is more proximal to the centre of rotation. However, as soon as we suspend legs anywhere more proximal than the knee region, the gymnast would start to get tangled with the cable that suspends the aid. To avoid this problem, another structure is needed, and therefore the practical simplicity of this type of aid will be lost. This dilemma has been tackled but not yet solved. For now, it would be most practical to understand the mechanical consequences of using a traditional and simple aid, to use it according to its aim in training in a variety of situations, and to integrate the aid training with other training that could compensate for the downside of the training with the aid.

Appendix C

Suggestions on Setting up a Suspended Aid

When a suspended aid is set up, it is important to consider the length of the cable and the mass of an aid. Considering the increase in the moment of inertia due to the mass of the aid, we believe that the mass of the aid should be as small as possible. The length of the cable, on the other hand, should be as long as possible to reduce the horizontal component with respect to the vertical component of the cable tension. However, it is often constrained by the height of a ceiling. In this study, the aid was attached to the beam running 4.1 m above the surface of the pommel horse. Despite the limited length of the cable, the horizontal component of the aid reaction force was actually very small (chapter four) because a centrifugal force for the mass of the aid counterbalanced the horizontal component of the cable tension. Given such results, it would be beneficial to provide a way of estimating a good balance between a centrifugal force for the rotation of the aid and the horizontal component of the cable tension.

As described in chapter four, the centrifugal force can be computed as:

$$F_{\text{cent}} = \frac{m \cdot v^2}{r}$$

where m is the mass of the aid (kg), v is the horizontal velocity of the aid (m/s), and r is the radius of the horizontal rotation (m). If we assume the horizontal rotation of the aid to be a perfect circle, the average velocity of the aid can be computed as:

$$\bar{v} = \frac{2\pi r}{t}$$

where t is the total duration for a single circle (s). Therefore, the average centrifugal force can be estimated as:

$$\bar{F}_{\text{cent}} = 4\pi^2 \cdot \frac{m \cdot r}{t^2}$$

When the average values for this study were substituted for each variable (r = 0.82 m, t = 1.72 s, m = 2.3 kg), the average centrifugal force is estimated to be 25.1 N. The computed centrifugal force in chapter four was 24.2 N on average.

On the other hand, the horizontal component of the cable tension can be estimated as:

$$F_{\text{cable-h}} = \frac{r}{h} \cdot F_{\text{cable-v}}$$

$$= \frac{r}{h} \cdot \left|F_{\text{leg-v}} + m \cdot g\right|$$

where $F_{\text{cable-h}}$ is the horizontal component of the cable tension (N), $F_{\text{cable-v}}$ is the vertical component of the cable tension (N), h is the height of the cone formed by the trajectory of the aid (m), and $F_{\text{leg-v}}$ is the vertical component of the force applied from the legs (N). With the average values in this study (r = 0.82 m, h = 3.9 m, $F_{\text{leg-v}}$ = 0.28 BW × 46.3 kg × 9.81 m/s^2 = 127.2 N), for example, the horizontal component of the cable tension is estimated to be 31.5 N. To have the minimal influence of horizontal forces during circles with a suspended aid, these two forces should cancel each other out. That is:

$$|F_{\text{cent}}| \approx |F_{\text{cable-h}}|$$

therefore,

$$m \approx \frac{F_{\text{leg-v}}}{\left(\frac{4\pi^2}{t^2} \cdot h - g\right)}$$

or

$$h \approx \frac{F_{\text{leg-v}} + m \cdot g}{\left(\frac{4\pi^2}{t^2} \cdot m\right)}$$

These equations can be useful to roughly estimate an appropriate setting for a suspended aid. Note that these equations are based on dynamic equilibrium between the horizontal component of the cable tension and the centrifugal force for the aid during circles. If the cable is too short due to a low ceiling, a large horizontal component of the cable tension makes it difficult to start circles.

It should also be noted that the force applied from the legs to the aid is not constant (see Figure 4-4). The minimal value of this force reached as low as 0.14 BW around the right-hand-release position, possibly in relation to the rightward lateral flexion of the body during that phase. The reduction of the force from the legs results in the decrease in the friction between the legs and the aid. For this study, the location of the aid was fixed on the legs with an elastic wrap during circles. This was one of the reasons why the gymnasts felt more comfortable with the suspended aid developed for this study than bucket-type aids that they had used. That is, they did not need to worry about losing the aid by the centrifugal force during circles. When a suspended aid is constructed, it is desirable to have some kind of structure to prevent the bucket from slipping off from the legs.