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Research article

Lower Extremity Muscle Activation and Kinematics of Catchers When Throwing Using Various Squatting and Throwing Postures

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Abstract
This study investigated the differences in joint motions and muscle activities of the lower extremities involved in various squatting postures. The motion capture system with thirty-one reflective markers attached on participants was used for motion data collection. The electromyography system was applied over the quadriceps, biceps femoris, tibialis anterior, and gastrocnemius muscles of the pivot and stride leg. The joint extension and flexion in wide squatting are greater than in general squatting ($p = 0.005$). Knee joint extension and flexion in general squatting are significantly greater than in wide squatting ($p = 0.001$). The adduction and abduction of the hip joint in stride passing are significantly greater than in step squatting ($p = 0.000$). Furthermore, the adduction and abduction of the knee joint in stride passing are also significantly greater than in step squatting ($p = 0.000$). When stride passing is performed, the muscle activation of the hamstring of the pivot foot in general squatting is significantly greater than in wide squatting ($p < 0.05$), and this difference continues to the stride period. Most catchers use a general or wide squatting width, exclusive of a narrow one. Therefore, the training design for strengthening the lower extremity muscles should consider the appropriateness of the common squat width to enhance squat-up performance. For lower limb muscle activation, wide squatting requires more active gastrocnemius and tibialis anterior muscles. Baseball players should extend the knee angle of the pivot foot before catching the ball.

Key words: Baseball, biomechanics, stride, electromyography, motion, kinetic chain.

Introduction

The catcher, an often-neglected player in a baseball game, should receive as much attention as a pitcher does in determining the factors involved in infield defense (Barzun, 1973). Barrett and Burton (2002) investigated seven collegiate baseball games and discovered that of all the balls thrown, 29% were from the catcher, second only to the pitcher (51%), and considerably higher than any other position (less than 5%). Most biomechanical studies have focused on the pitcher's upper (Dun et al., 2007; Escamilla et al., 2007; Fleisig et al., 2006; Mullaney et al., 2005; Murray et al., 2001; Pedegana et al., 1982; Sabick et al., 2004; Stodden et al., 2005; Werner et al., 1993; Werner et al., 2007; Wright et al., 2006) and lower extremities (Elliott et al., 1988; MacWilliams et al., 1998), but only two studies have focused on the catcher (Larson et al., 2007).

Sakurai (1994) examined the biomechanics of catchers by using two high speed cameras, and found similar kinematic data in various age groups. The probability of stealing bases is often considered an index for catcher assessment (Loughin and Bargen, 2008). A catcher who prevents a runner from stealing bases throws the ball after rising from a squatting posture. Thus, squatting throwing is the most representative motion of catchers and the primary motion of related studies. Larson et al. (2007) investigated the differences between a catcher-pivot throwing motion and a weight-shift throwing motion. They found the maximum ground reaction force (GRF), the time to maximum ground reaction force, and the rate of force development of the weight-shift throwing motion were larger than those of the pivot throwing motion ($p < 0.05$). In addition to throwing in a squatting posture, the catcher in a game or during training must also squat for long periods. The joint loadings of the lower extremities are larger than those of the upper extremities used in other positions. However, studies related to the lower extremities of catchers are lacking.

Fortenbaugh (2010) discovered that compared with other positions, catchers had greater elbow flexion, reduced pelvic-trunk rotation, and a shorter stride. H. Plummer and Oliver (2013) investigated the throwing kinematics and kinetics of catchers at two age levels. Older catchers were found to have greater shoulder elevation at ball release and significantly greater shoulder external rotation at foot contact and shoulder maximum external rotation than younger catchers had. Older catchers also demonstrated greater shoulder moment at each specific timing, except at the maximum external rotation, and greater elbow moment at each specific timing, except at foot contact. Plummer and Oliver (2014) examined the relationship between throwing kinematics and gluteal muscle activation. Their results demonstrated two significant inverse relationships at foot contact. One was between stride leg gluteus maximus activity and pelvis axial rotation, and the other was between trunk axial rotation and pelvis lateral flexion. Moreover, a significant positive relationship existed between drive leg gluteus maximus activity and trunk flexion. However, other muscles in the lower extremity that are also considered crucial in contributing to the squat-up motion were not investigated.

Dynamic squat involves multiple joints of the lower extremities (Bynum et al., 1995; Escamilla et al., 1998) and is often used to train the lower muscle groups in exercise training (O'Shea, 1985). Among the joints of the

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lower extremities, the range of motion of the knee joint is the largest, and depending on the flexion angle, the dynamic squat can be divided into the half squat and deep squat. Nagura et al. (2002) indicated the largest ranges of knee motion during double leg descending and ascending is approximately 150°. The net flexion moment and net posterior force of the knee during single and double leg descending and ascending were both significantly larger than were other routine motions. Escamilla et al. (2001) examined various squatting posture widths and discovered that wide squatting limited the angle of the knee and hip joint, causing the trunk to have larger motion in the general squat. They also observed differences in the gastrocnemius, gluteus maximus, and adductor longus during wide squatting.

Research on catcher motion is incomplete, and the role of the lower extremities during catcher throwing in a squatting posture is unclear. No objective results have been obtained to provide coaches and players a reference regarding the influence of squatted throwing involving various squatting posture widths and different approaches for delivering the ball. Therefore, this study targeted the catcher in order to clarify motion dissimilarities when throwing with various squatting posture widths and techniques for delivering the ball. We investigated the differences in joint motions and muscle activities of the lower extremities involved in various squatting postures.

Methods

Twelve baseball catchers were recruited for the study (ages: 18.9 ± 2.8 y, height: 1.70 ± 0.06 m, weight: 80.8 ± 7.9 kg, and experience: 8.3 ± 2.7 y). All participants reported no history of low back pain or other musculoskeletal problems within the previous 3 years and were required to complete a questionnaire with a complementary interview regarding the practice of physical and sporting activities prior to the trial. The study protocol was approved by the National Cheng Kung University Hospital Human Experiment and Ethics (ER-98-095), and all participants signed committee-approved informed consents.

For kinematic analysis, 31 reflective landmarks were attached to the sternal notch, processus xiphoideus, spinous process of the seventh cervical vertebra, left and right acromioclavicular, lateral epicondyle of the humerus, midpoint of the radial and ulnar styloid process, sacrum, anterior superior iliac spine, lateral aspect of the thigh, lateral and medial knee joint line, lateral aspect of the shank, lateral and medial malleolus, and the second metatarsal head and heel, according to the International Society of Biomechanics recommendation for reporting human joint motion (Wu, et al., 2002; 2005). An eight-camera Expert Vision Raptor motion analysis system (Motion Analysis Corp., Santa Rosa, CA, USA) was used to collect the position of the reflective markers at a sampling rate of 500 Hz. The light emitting diode digital camera captured the analog signal from the reflective markers through a video and analog signal processor (IBM PC-AT). At least two cameras captured each reflective marker. The marker data of the recorded motion were smoothed using Woltring's generalized cross-validation natural spline filter. The surface electrodes of the MA300 electromyography (EMG) system (MA300, Motion Analysis Corp., U.S.A.) were applied over the quadriceps, biceps femoris, tibialis anterior, and gastrocnemius muscles of the pivot and stride leg. Prior to application of the electrodes, both electrodes and the skin of the application sites were cleaned with alcohol and a razor as necessary. A 5-s isometric maximum contraction was performed for each muscle or muscle group using the maximum manual muscle strength test (MMT) prior to the experimental trials to obtain the maximum EMG level of the selected muscles for normalization. Finally, EMG parameters were calculated as a percentage of maximal voluntary isometric contraction (MVC; unit: % MVC).

A 3 × 5-m sports space was stipulated by the range of motion. A 50 × 50-cm pitching active area was set to determine an effective pitch. Kinematics data at a general-stance and a wide-stance during the pivot throwing motion and weight-shift throwing motion were initially collected.

1. General-stance (Figure 1-left): Participants stand with feet apart at an approximate shoulder width and point squat toes straight forward.

2. Wide-stance (Figure 1-right): Participants stand with feet apart at a width wider than shoulder-width, and point squat toes straight forward.

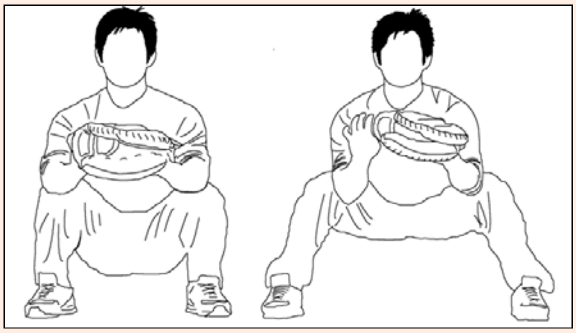

Figure 1. General stance (left) and wide-stance (right) of the catcher.

3. Pivot throwing motion (Figure 2): Participants squat to prepare for catching the ball with the pivot foot (right foot) on the first force plate. The researcher throws the ball to participants when the data collection begins. Participants catch the ball and the pivot foot supports this action simultaneously by ascending. The stride phase begins with the foot contacting the ground, followed by the acceleration (from maximum shoulder external rotation angle to ball release), ball release, and follow-through phases. The ball is then thrown into the target area.

4. Weight-shift throwing motion (Figure 3): Participants squat to prepare for catching the ball, with the pivot foot (right foot) on the first force plate. The researcher throws the ball to participants when the data collection begins. Participants catch the ball and the pivot foot supports this action (the pivot-foot steps on the second force plate) simultaneously by ascending. The stride phase begins with the stride foot contacting the ground, followed by the acceleration, ball release, and follow-

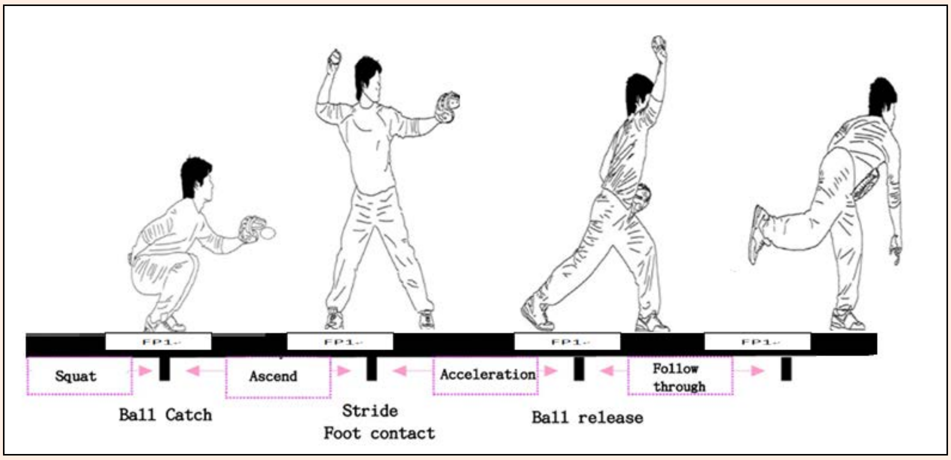

Figure 2. **Phases of pivot throwing motion.**

through phases. The ball is then thrown into the goal net.

All participants were asked to perform two throwing types with two squat positions (general-stance and wide-stance), respectively. Five successful trials for each type were collected.

SPSS statistical software (SPSS Inc., USA) was used in this study for statistics and analysis. Different squat widths and throwing types (joint angles) were determined using two-way analysis of variance and repeated measures. The paired *t* test was used to analyze the kinematics parameters and the muscle activity of various squat widths and throwing types during different throwing-motion phases. A statistical significance level was set at $p < 0.05$. All kinematics and muscle activity parameters were translated into graphs and tables by using Origin 8.0 software.

Results

For throwing, the pivot throwing was the highest (58.3%), followed by a mixture of various throwing activities (33.3%). The weight-shift throwing was the lowest (8.3%). For typical squatting width, most catchers used the general squatting position (75.0%), whereas others used the wide-squatting position (25%) when no one was on base. However, most catchers used the wide-squatting position (83.3%), when someone was on base. The average ball speed in pivot throwinging with various squatting widths (general squatting: 29.36.± 3.63 m·s^{-1}; wide squatting: 27.81 ± 2.81 m·s^{-1}) was greater than that in step throwing (general squatting: 25.734. ± 2.03 m·s^{-1}; wide squatting: 24.71 ± 2.61 m·s^{-1}) (p = 0.000).

Table 1 shows the joint motion for various squatting and throwing widths from the pivot foot and stepping foot. The joint extension and flexion in wide squatting were greater than in general squatting (p = 0.005). Knee joint extension and flexion in general squatting were significantly greater than in wide squatting (p = 0.001). Ankle joint activity was not influenced by various squatting widths in the pivot foot. The throwing technique was influenced by the joint activity of the pivot foot. The adduction and abduction of the hip joint in pivot throwing were significantly greater than in step squatting (p = 0.000). Furthermore, the adduction and abduction of the

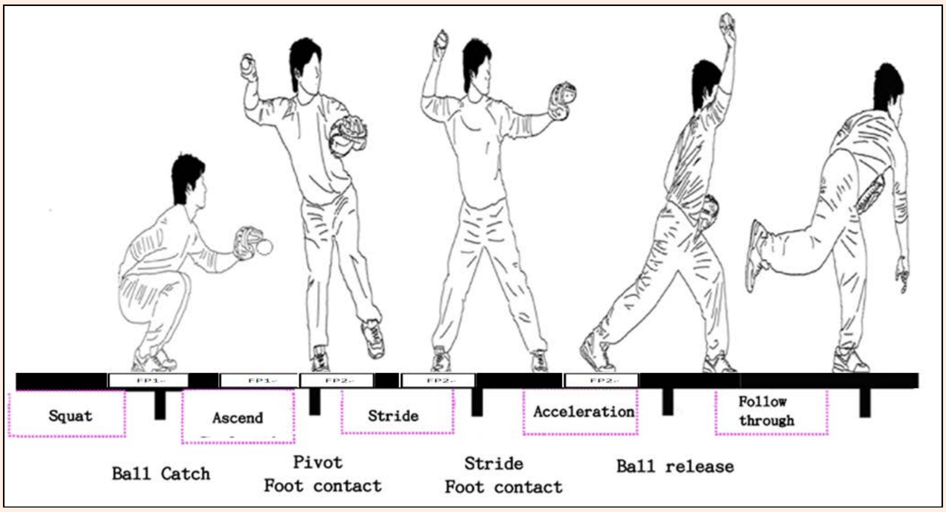

Figure 3. **Phases of weight-shift throwing motion.**

Table 1. The joints angle and ROM on pivot foot of different squat width and throwing type (deg). Data are means (±standard deviation).

Movement	General-stance Pivot	General-stance Weight-shift:	Wide-stance Pivot	Wide-stance Weight-shift:	Significant source	F(1,11)	p-value	Notes
Pivot foot								
Hip								
Flex/Ext	116.6 (11.1)	118.3 (11.9)	127.0 (12.6)	129.7 (15.2)	Squat width	11.987	.005	Wide＞General
Abd/Add	35.7 (7.9)	44.5 (6.7)	34.9 (6.8)	45.3 (6.9)	Throwing type	29.723	.000	Weight-shift＞Pivot
Rotation	55.8 (10.0)	64.4 (14.4)	30.7 (9.2)	35.6 (8.2)				
Knee								
Flex/Ext	106.9 (9.4)	105.8 (15.9)	96.6 (9.1)	86.6 (14.5)	Squat width	20.774	.001	General＞Wide
Abd/Add	27.1 (7.6)	37.2 (10.9)	27.1 (9.6)	36.5 (9.8)	Throwing type	70.550	.000	Weight-shift＞Pivot
Rotation	37.1 (11.6)	37.3 (12.0)	33.2 (11.8)	35.0 (15.5)				
Ankle								
DorFlex/PlaFlex	53.4 (11.1)	56.9 (11.0)	55.0 (11.4	56.7 (12.7)				
Inv/Ever	24.6 (7.9)	28.6 (6.8)	25.1 (8.8)	27.0 (8.1)				
Rotation	34.1±10.7	37.6 (10.7)	30.7 (9.2)	35.6 (8.2)				
Stride foot								
Hip								
Flex/Ext	61.5 (11.6)	92.7 (13.9)	78.1 (17.3)	113.2 (15.5)	Squat width Throwing type	30.621 140.348	.000 .000	Wide ＞General Weight-shift＞Pivot
Abd/Add	61.4 (5.8)	59.4 (5.6)	60.9 (6.5)	60.3 (3.1)				
Rotation	54.3 (17.7)	71.0 (12.7)	50.9 (12.3)	67.7 (11.4	Throwing type	35.899	.000	Weight-shift＞Pivot
Knee								
Flex/Ext	105.7 (11.0)	114.6 (16.8)	90.1 (10.7)	97.3 (14.3)	Squat width Throwing type	48.216 14.842	.000 .003	General＞Wide Weight-shift＞Pivot
Abd/Add	28.1 (6.8)	33.2 (8.9)	27.5 (8.7)	31.2 (9.2)	Throwing type	10.355	.008	Weight-shift＞Pivot
Rotation	42.6 (19.3)	45.7 (22.1)	37.5 (12.9)	38.9 (17.5)				
Ankle								
DorFlex/PlaFlex	44.8 (10.6)	53.1 (9.9)	50.1 (10.6)	54.7 (8.7)	Throwing type	27.362	.000	Weight-shift＞Pivot
Inv/Ever	28.5 (9.1)	27.6 (6.4)	22.2 (7.2)	23.2 (7.0)	Squat width	17.308	.002	General＞Wide
Rotation	30.5 (15.5)	30.9 (6.6)	29.0(9.2)	28.4 (4.8)				

Flex/Ext = Flexion/Extension; Abd/Add = Abduction/Adduction; DorFlex/PlaFlex = Dorsiflexion/Plantarflexion; Inv/Ever = Inversion/Eversion

knee joint in pivot throwing were also significantly greater than in step squatting ($p = 0.000$). The extension and flexion of the hip joint in wide squatting were greater than in general squatting ($p = 0.000$), and the extension and flexion of the knee joint in general squatting were greater than in wide squatting ($p = 0.000$). Furthermore, the extension and flexion of the ankle joint in general squatting were greater than in wide squatting ($p = 0.002$).

Table 2 shows that for the squatting motion in wide squatting, the muscle activation of the gastrocnemius, tibialis anterior, and hamstring was significantly greater than in general squatting ($p < 0.05$), and that of the gastrocnemius, tibialis anterior, and quadriceps of the stepping foot was significantly greater than in general squatting ($p < 0.05$). Following the stepping-up period (from ball catch to pre-acceleration phase), the muscle activation of the hamstring in wide squatting was greater than in general squatting. At the acceleration phase, the muscle activation of the tibialis anterior muscle in general squatting was significantly greater than in wide squatting ($p < 0.05$). In the stepping-up period, the muscle activation of the quadriceps in general squatting was relatively greater than in wide squatting ($p < 0.05$). In the stepping-up period, the muscle activation of the quadriceps in wide squatting remained significantly greater. In the stepping-up period, the muscle activation of the tibialis anterior muscle of the stepping foot in general squatting was significantly greater. This significant difference continued in the acceleration phase (Figure 4).

Discussion

This study investigated the differences in joint motions and muscle activities of the lower extremities among various squatting postures involved in the baseball-catching motion.

We found a significant difference in foot distance between the two squatting postures, and a wide stance (193.34. ± 20.81% shoulder width) in approximately 65% of the acromion width that was wider than the general stance (127.48 ± 22.98% shoulder width). Most previous studies have attempted to determine how squatting affects the lower-limb angle and muscle activation. Squatting can be defined by shoulder width (Escamilla et al., 2001; McCaw and Melrose, 1999), the distance between the two anterior superior iliac spines (Escamilla, et al., 2001), or the distance between the two greater trochanters (Paoli et al., 2009). The previous definition of wide stance was approximately 140% to 196% of shoulder width, or 200% of the distance between the two greater trochanters. The wide stance adopted in this study is in accordance with the earlier definition. The general definition of general stance is typically 75% to 118% of shoulder width, or 100% of the distance between the two greater trochanters. However, the general stance adopted by the catcher was 127% of shoulder width on average and was categorized

Table 2. The Maximum voluntary muscle contraction on pivot foot of different squat width in pivot throwing motion (%MVC). Data are means (±standard deviation).

Muscle	Phase	Pivot throwing General-stance	Pivot throwing Wide-stance	p-value	Notes	Weight-shift: General-stance	Weight-shift: Wide-stance	p-value	Notes
					Pivot foot				
GASTRO	Squat *	22.8 (7.3)	35.1 (14.0)	.039	wide＞general	29.4 (12.9)	30.1 (11.0)	.818	NS
	Ascending	92.2 (10.3)	91.0 (9.8)	.801	NS	102.1 (10.3)	97.1 (23.8)	.435	NS
	Stride					93.6 (15.0)	100.5 (16.0)	.360	NS
	Acceleration	92.4 (13.7)	83.4 (15.0)	.170	NS	85.8 (16.2)	89.8 (23.3)	.650	NS
	Follow through	16.3 (7.8)	12.0 (4.7)	.129	NS	14.2 (5.4)	12.3 (3.3)	.238	NS
TIB ANT	Squat *	51.4 (17.4)	74.0 (16.2)	.005	wide＞general	50.2 (16.5)	58.6 (12.8)	.201	NS
	Ascending	73.6 (11.8)	75.5 (14.3)	.413	NS	63.3 (8.1)	63.9 (7.8)	.830	NS
	Stride					76.4 (7.8)	67.7 (19.8)	.141	NS
	Acceleration *	32.7 (13.6)	19.6(11.0)	.024	general＞wide	33.2 (9.0)	24.9 (12.0)	.038	general＞wide
	Follow through	7.8 (6.9)	7.0 (4.0)	.719	NS	10.5 (3.7)	13.1 (8.6)	.252	NS
BIC FEM	Squat *	34.5 (17.0)	71.0 (16.0)	.000	wide＞general	74.9 (9.4)	47.7 (15.3)	.001	general＞wide
	Ascending *	102.2 (28.0)	127.1 (29.8)	.038	wide＞general	111.0 (24.0)	70.5 (10.4)	.000	general＞wide
	Stride					143.0 (19.4)	128.4 (20.7)	.096	general＞wide
	Acceleration	132.2 (26.1)	141.9 (26.5)	.273	NS	131.0 (15.5)	142.6 (38.4)	.341	NS
	Follow through	43.6 (20.3)	42.3 (20.3)	.825	NS	42.3 (16.9)	28.4 (12.7)	.009	wide＞general
QUAD	Squat	42.5 (12.2)	42.9 (9.2)	.919	NS	51.7 (15.6)	53.2 (22.0)	.812	NS
	Ascending *	43.1 (12.2)	32.9 (4.0)	.030	general＞wide	84.9 (16.4)	65.7 (16.9)	.008	general＞wide
	Stride					53.0 (21.8)	50.6 (22.4)	.690	NS
	Acceleration	15.3 (6.0)	19.6 (9.3)	.127	NS	17.6 (11.5)	21.8 (14.3)	.366	NS
	Follow through	9.1 (9.8)	7.8 (3.8)	.649	NS	13.8 (5.0)	17.4 (10.9)	.273	NS
					Stride foot				
GASTRO	Squat *	47.5 (15.9)	74.2 (13.9)	.000	wide＞general	64.7 (18.4)	44.4 (15.9)	.008	general＞wide
	Ascending	112.9 (21.4)	91.4 (24.7)	.069	NS	100.5 (12.5)	100.8 (23.5)	.974	NS
	Stride					88.8 (19.1)	99.9 (19.4)	.095	NS
	Acceleration	58.2 (18.4)	50.4 (15.3)	.247	NS	74.8 (24.3)	67.2 (29.2)	.454	NS
	Follow through	30.2 (9.1)	42.4 (21.6)	.085	NS	50.1 (23.3)	39.4 (6.3)	.136	NS
TIB ANT	Squat *	19.7 (8.3)	48.3 (10.1)	.000	wide＞general	44.6 (10.6)	37.2 (6.9)	.107	NS
	Ascending *	69.8 (9.6)	45.4 (10.9)	.000	general＞wide	52.6 (12.0)	48.1 (17.4)	.507	NS
	Stride					44.9 (8.8)	42.6 (12.0)	.571	NS
	Acceleration *	57.0 (14.8)	32.9 (14.1)	.002	general＞wide	33.8 (13.6)	33.5 (10.0)	.934	NS
	Follow through	18.7 (10.5)	18.6 (7.2)	.965	NS	16.6 (4.2)	16.0 (6.1)	.766	NS
BIC FEM	Squat *	87.2 (11.4)	54.9 (8.0)	.000	general＞wide	74.4 (19.4)	57.8 (18.0)	.034	general＞wide
	Ascending *	45.0 (11.6)	41.7 (13.0)	.546	NS	54.6 (15.7)	44.8 (16.8)	.029	general＞wide
	Stride					36.2 (9.8)	33.1 (12.3)	.362	NS
	Acceleration	39.5 (14.6)	29.0 (11.0)	.086	NS	38.0 (11.8)	42.3 (21.2)	.467	NS
	Follow through	30.7 (12.8)	28.3 (9.9)	.493	NS	33.3 (12.7)	37.9 (18.9)	.478	NS
QUAD	Squat *	25.6 (5.5)	45.4 (10.2)	.000	wide＞general	88.3 (10.7)	37.2 (12.2)	.000	general＞wide
	Ascending *	94.2 (22.5)	103.8 (22.8)	.170	NS	85.2 (13.3)	67.0 (18.0)	.002	general＞wide
	Stride					101.9 (25.1)	102.2 (15.3)	.965	NS
	Acceleration	117.9 (33.2)	131.2 (33.1)	.184	NS	118.2 (21.6)	110.7 (17.2)	.210	NS
	Follow through	20.1 (9.6)	18.2 (4.0)	.527	NS	16.4 (5.2)	16.1 (7.7)	.918	NS

GASTRO = Gastrocnemius; TIB ANT = Tibialis anterior; BIC FEM = Biceps femoris; Quadriceps * $p < 0.05$; NS: no significant.

in previous studies.

The time of the pick-off throwing by the catcher and the pitcher's pitching speed are equally relevant, and are both indices for skills evaluation. Previous studies have found that, in dynamic squatting, the increase in rising time is consistent with squatting (Escamilla et al., 2001), and rising time can be decreased by lowering the knee flexion angle through the support of the catchers' knee saver (Hsieh, 2007). Previous studies have suggested that squatting and the knee flexion angle are crucial factors in action duration. However, the results of this study did not show any correlation between squatting and ball-throwing time for both pivot throwing and weight-shift throwing. Further investigation revealed a larger range of motion of the hip flexion/extension angle in wide stance and the knee flexion/extension angle in general stance. In wide stance, the higher hip flexion angle compensated for the lower knee flexion angle, cancelling any effect on weight-shift throwing. However, in contrast to the results of Escamilla et al. (2001), no increase in action duration was observed in wide stance. Loading might be a reason Escamilla et al. (2001), complicating action duration, and a change of body weight or muscle strength caused by loading must be considered. Hence, we observed no increase in action duration in wide stance because extra loading was absent.

Higher ball speed was found in weight-shift throwing in both forms of squatting, although previous studies

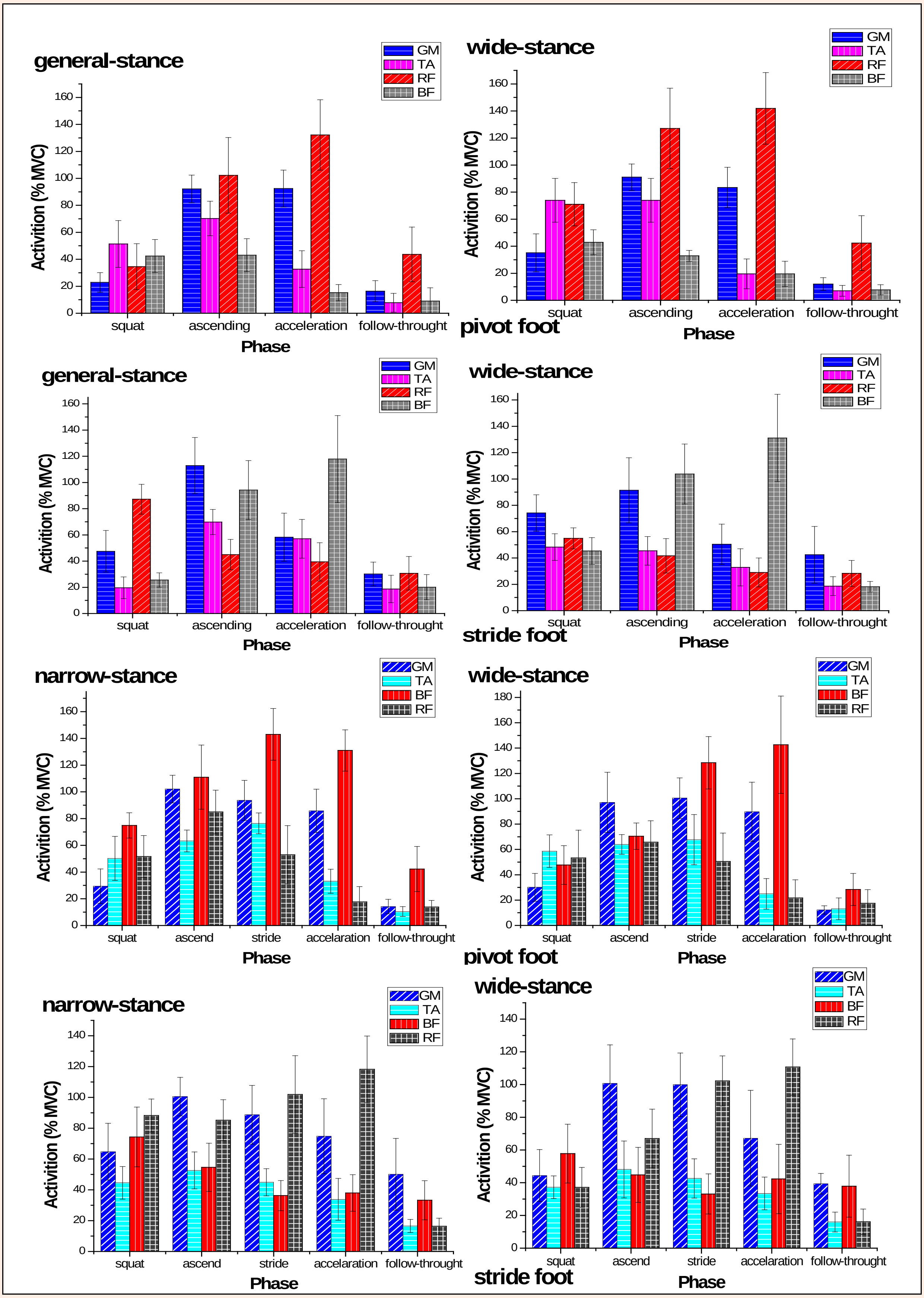

Figure 4. **The electromyography analysis of lower limb on pivot foot of general-stance and wide-stance in weight-shift throwing motion (GM: Gastrocnemius; TA: Tibialis anterior; RF: Rectus femoris; BF: Biceps femoris).**

as medium stance (100% to 153% of shoulder width or 150% of the distance between the two greater trochanters) have not shown any ball throwing speed (Larson et al., 2007). A possible explanation for higher ball speed in weight-shift throwing might lie in the ground reaction force, lower-limb joint angle, and muscle activity. MacWilliams et al. (1998) reported that the linear wrist velocity of the throwing arm is positively related to the upward-forward ground reaction force and total force at the pivot foot. Previous studies on the lower-limb joint angle and muscle activation have shown the contribution to push-off by hamstrings (Yu et al., 2008), and the greatest hamstring activation occurs at a knee joint flexion angle of 50° to 70° (Escamilla et al., 1998; 2001; Ninos et al., 1997). We identified that the greatest hamstring activation in the pivot foot appeared at the stride phase to push off and generate the driving force. The knee joint flexion angle in the stride phase of weight-shift throwing began at approximately 90° and ended at 60°. Weight-shift throwing caused the flexion angle for greatest hamstring activation in the midst of the stride phase and pivot throwing occurred directly after the stride phase, which is a possible reason for the higher ball speed in weight-shift throwing.

In pivot throwing, the most distinct difference in joint angles of the two squatting postures in each phase was at the squat phase and ascend phase. In the squat phase, the joint angle difference occurred from the stance and continued to the ascend phase. The general stance had a significantly higher knee joint flexion angle at squatting, and the angle remained high upon ascending. The hip joint flexion angle in wide stance was higher in squatting and higher than that of general stance at approximately 5° on average in the ascend phase. The acceleration and follow-through phases did not reveal how the next phase (ascend phase) was affected by the former phase (squat phase). Despite the difference in the early stage, when the catcher throwed the ball in the acceleration phase (from the stride foot contact to the ball release), the lower-limb joint angles and joint motion in different squatting were similar. In the acceleration phase of pivot throwing, the hip joint angle at the pivot foot was approximately 52° and 32° in the knee joint, whereas the hip joint angle at the stride foot was 75° and 50° in the knee joint. Between the two squatting postures, the difference in lower-limb joint angles was less than 2°, and compared with that of the knee flexion angle when the pivot foot of pitchers entered the acceleration phase (the instance when the stride foot makes contact), Escamilla et al. (2007) found the instant knee flexion angle to be approximately 47° for pitchers, which was similar to the knee flexion angle in the acceleraion phase in the present study. The angular velocity of the stride foot in each pivot-throwing phase showed little difference between various squatting postures. Compared with previous studies, we concluded that, regardless of the difference in the early stage of throwing, the stride foot entered the acceleration phase with an analogus knee angle; and regardless of squatting, the stride foot shared an identical joint motion.

Squatting affected only joint angles in the early stages (squat and ascend phases) of weight-shift throwing. In the acceleration phase of weight-shift throwing, the lower-limb joint angles at the pivot foot were 34° at the hip and 36° at the knee, and the joint angles at the stride foot were 75° at the hip and 40° at the knee. The comparison of lower-limb joint angles in the acceleration phase between pivot and weight-shift throwing showed a greater extension. Although different lower-limb joint angles appeared in various squatting and lower-limb motions presented in different throwing approaches, the stride foot entered the acceleration phase with the hip joint flexion angle at approximately 75°. Previous studies on pitching have concluded that the function of the pivot foot is to support the body weight and to maintain balance during pitching (MacWilliams, et al., 1998). For catcher throwing, the stride foot entered the acceleration phase at 75° of the hip joint flexion angle, which may be an appropriate angle for balancing throwing.

Plummer and Oliver (2014) indicated that the gluteal muscle group provided squat-up and pelvic stability functions from the squatting position to the acceleration phase. This study revealed that the driving force generation of the pivot foot in the stride phase is due to hamstring contraction. This is consistent with the finding of a previous study that hamstrings contributed to the push-off motion (Yu et al., 2008), and that the gluteal muscle group helps to extend the pelvic joint, provides energy to squat up, and pelvic stability during acceleration. Hamstrings generate the energy to drive the throwing motion to the second base. The results of Plummer and Oliver (2014) and of the present study provide a clearer insight into the contribution of the lower extremity muscles during the throwing motion.

In pivot throwing, greater activation of the gastrocnemius, tibialis anterior, and hamstrings appeared in the pivot foot in wide stance, whereas the stride foot demonstrated greater activation of the gastrocnemius, tibialis anterior, and quadriceps femoris in wide stance, suggesting that adopting the wide stance in pivot throwing maximizes muscle activation in the lower limb. From the lower-limb kinematics perspective, previous studies have revealed the greatest muscle activation in the quadriceps femoris, hamstrings, and gastrocnemius at knee flexion angles of 80° to 90° (Escamilla et al., 2001; Isear et al., 1997; Ninos et al., 1997; Signorile et al., 1994; Stuart et al., 1996), 50° to 70° (Escamilla et al., 1998; 2001; Wilk et al., 1996), and 60° to 90° (Escamilla et al., 1998; Isear et al., 1997), respectively. The knee flexion angle in wide stance of weight-shift throwing was found to be similar to the flexion angle for maximum muscle activation; thus the catcher could have greater muscle activation in wide stance.

A similar difference in squatting positions occurred in weight-shifting throwing. The pivot foot in general squatting displayed greater hamstring muscle activation whereas the stride foot in general squatting displayed greater gastrocnemius, hamstring, and quadriceps femoris muscle activation. Various throwing motions in the squatting position showed reverse muscle activation of the lower extremity. Through the knee flexion angle of weight-shifting throwing, the knee joint showed an obvious extension at the ball-catch instant. Taking the pivot foot as an example, at the onset of the squat phase, the knee flexion angle of the general squat and the wide squat were 140° and 128°, respectively. However, at the ball-catch instant, they were 127° and 107°. Although significant differences were found in the knee joint angle of various squatting positions, the knee joint did not show early extension at the ball-catch instant. This might explain the reverse muscle activation of the lower extremity in various squatting positions and throwing motions.

According to MacWilliams et al. (1998), the pivot foot generated a forward-driving GRF, initializing the momentum toward the throwing direction. The results of the muscle activation of the pivot foot indicated that the generation of the driving force of the pivot foot in the stride phase resulted from hamstring contraction. This is consistent with a previous study that reported that hamstrings contribute to the push and step motion (Yu et al., 2008).

Although the hamstrings began to show larger activation in the stride phase, we also found that when entering the acceleration phase, hamstrings showed maximum muscle activation. However, the driving force of the pivot foot in various throwing motions did not increase continually in the acceleration phase. This was because when the pivot foot completed the push and step motion, it immediately left the ground. Therefore, even the larger muscle activation of the hamstrings could not contribute to the driving force. Therefore, the driving force generation of the pivot foot in the stride phase resulted from hamstring contraction. The pivot throwing subsequently displayed a lower driving force. The knee angle at maximum muscle activation of the hamstrings was 50° to 70° (Escamilla, et al., 1998; 2001; Ninos, et al., 1997).

The knee flexion angle of the pivot foot during pivot throwing was 125° at the onset and 70°at the end of the stride phase. For maximum muscle activation of the hamstrings, maximum activation occurred at the end of the stride motion. However, for weight-shift throwing, the angle was 90° at the onset and 60° at the end of the stride phase. The maximum muscle activation of the hamstrings occurred at the middle of the stride phase. Therefore, the weight-shifting motion resulted in larger knee extension of the pivot foot, so that hamstrings reached maximum muscle activation earlier in the stride phase, possibly generating more driving force. For the measured GRF from the force plate, a driving force of only 0.3 body weight was found in the stride phase of weight-shift throwing, lower than the 0.4 body weight of pivot throwing. This might be because in weight-shift throwing, the stride motion lagged behind the weight-shifting motion, and the ground contact time of the pivot foot after weight shifting decreased because of gravity. Hence, a contradictory situation occurred. Another possibility might be that after the weight-shifting motion in the weight-shift throwing and directly before the knee flexion angle of the maximum hamstring activation, a driving force of 0.3 body weight was the optimal performance.

Conclusion

Baseball catchers require great effort in moving and balancing their body motion in wide squatting. Various squatting positions do not affect the time required for the throwing motion, but longer action duration of the weight-shift throwing motion generates more power and faster ball speed. The major factor influencing throw-type choices in various squatting positions is the starting phase during the throwing motion.

In the acceleration phase, the lower limbs demonstrate similar patterns in various squatting positions and throw types. The stride foot in the acceleration phase maintains a consistent hip-joint angle to support the weight of the ball movement and body balance. Weight-shift throwing motions achieve twice the forward driving force, and faster ball speed. Knee extension at the ball-catch instant in weight-shift throwing resulted in maximum muscle activation of the hamstrings of the pivot foot during the stride phase. This directly influenced the driving force of the pivot foot.

This study can serve as a reference for future studies. Most catchers use a general or wide squatting width, instead of a narrow squatting width. Therefore, the training design for strengthening the lower extremity muscles should consider the appropriateness of the common squat width to enhance squat-up performance. No difference existed in the throwing motion time between general squatting and width squatting. For lower limb muscle activation, wide squatting requires more active gastrocnemius and tibialis anterior muscles. Baseball players should extend the knee angle of the pivot foot before catching the ball.

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Key points

- Common squatting width can enhance squat-up performance through strengthening lower body muscle.
- Wide squatting width might improve lower body muscle activation, leading to more effective communication between the brain and the muscle group. The benefit might be improved coordination of lower body muscle.
- Common and wide squatting width might be cycled through training to enhance the strengthen and coordination of the lower body muscle, respectively.

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