Emergence of single and double peaks in individual force-time curves of the counter-movement jump (CMJ)

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Abstract

The force-time curves of countermovement jumps (CMJ) are often analyzed in jump diagnostics in order to draw conclusions about the quality of the jump. A distinction is often made between one- and two-peaked (also called "unimodal" and "bimodal") curves, but there is little research on the angular movements in the lower body that cause them. To fill this research gap, the present study recorded three different variants of the CMJ in two subjects using both a force plate and a motion capture system (n = 12 jumps). It could be shown that the two peaks resulted firstly from the fact that ankle plantar flexion started later than hip and knee extension and secondly that hips and knees were accelerated less at the beginning of the upward movement and more strongly in the further course until take-off. Regarding the jump variants, the greatest jump heights were obtained when the jumpers either chose their individual execution or tried to complete the jump as smooth as possible, which both produced two-peaked curves. If the countermovement was performed as quickly as possible, one-peaked force-time curves were generated, and lightly smaller jump heights were achieved. The theoretical considerations that single-peaked curves stand for an optimal intersegmental coordination and therefore should lead to better jump heights are contradicted by the empirical findings. The study contributed to explaining how two-peaked curves emerge. This should be of some importance for both researchers and coaches for this diagnostic jump, which is very relevant in many sports.

Keywords

jump diagnostics, force plate, motion analysis, angular velocity, coordination

1 Introduction

Jump diagnostics are part of the standard repertoire of performance diagnostics in many sports (Wank, 2021). The possibility of recording force-time curves using force plates raises the question from both researchers and practitioners' perspectives as to which characteristics enable an optimal jump. Possible criteria include different force parameters and the shape of the produced curves during the eccentric and concentric phases of the jump. Interrelations were found between different types of execution of the countermovement jump (CMJ) and force parameters. Fast countermovement velocities led to higher forces than slower countermovement velocities (Floría et al., 2016; Pérez-Castilla et al., 2021). Concerning the depth of the countermovement, Salles et al. (2011), Mandic et al. (2016) as well as Pérez et al. (2021) found that shorter depths were associated with higher maximal forces. Regarding the shape of the force-time curve, shorter countermovements showed one force peak, whereas larger ones showed two peaks (Pérez-Castilla et al., 2021). With this phenomenon that the force-time curve in CMJs has one or two peaks, also referred to as unimodal and bimodal in some studies, a lot of research is concerned. For example, in a study by Lake and McMahon (2018), when performing multiple trials, about two-thirds of the athletes consistently showed a bimodal shape in the force-time curve, just over ten percent had a single-peaked curve, and more than 20% were inconsistent. Summarizing the state of research, jumps with two force peaks had longer durations, a larger hip, knee, and ankle flexion resulting in a greater downward movement of the center of mass (COM), and produced lower forces, when compared to one-peaked curves (Kennedy & Drake, 2018; Kurz, 2011; McMaster, 2016; Peng et al., 2019). Some studies also looked at how different types of execution of the CMJ were related to vertical jump performance. With a fast countermovement velocity a comparable jump height as with a self-selected countermovement velocity could be reached in the study of Pérez-Castilla et al. (2021). While Salles et al. (2011), Gheller et al. (2015), and Peréz et al. (2021) found that a smaller countermovement depth resulted in less jump height than a larger or self-selected one, Mandic et al. (2015) showed that varying countermovement depth within a wide range of 25 cm around the athletes' preferred value revealed only small changes in jumping height. The results on the interrelation between single and double peak curves and jumping performance are not entirely consistent either. Some found positive associations of two-peaked curves with jump height (McMaster, 2016; Peng et al., 2019), some found no significant relations (Kennedy & Drake, 2018; Kurz, 2011). Overall, we have some evidence about parameters that affect the force-time curve and jump height in CMJs. A precise analysis of the type of movement execution that results in two-peaked curves and whether individual jumpers produce different curves as a result of different instructions is not very well known. Therefore, the aim of our study was to investigate different variants of the CMJ and their effects on the jump height and the force-time curves produced. A particular focus was to be placed on the course of the angular velocities of the mainly involved ankle, knee, and hip joints. In this way, the connection between the production of one- or two-peaked force-time curves and the coordination of the impulses, which has hardly been described to date, should also be clarified.

2 Methods

2.1 Procedures

The study design was a cross-sectional analysis based on two test persons. They were tested one after the other. The entire session took about 35 minutes per person. The athlete put on a motion capture suit (see below) and the experimenter attached the 17 sensors to the suit. After calibrating the sensors, a few easy practice jumps were performed to familiarize the athlete with the suit and force plate (see below) and to make any final adjustments. The test was preceded by a standardized 10-minutes warm-up program under the direction of the experimenter, which was intended to increase neuromuscular performance and reduce the risk of injury. It consisted of a brief general warming up and activation of the cardiovascular system through light aerobic work. Further, the muscle groups that were subsequently used were stretched dynamically through gymnastics and the corresponding joints were mobilized. In addition, a few submaximal repetitions of the CMJ were performed to prepare for the maximal load in the test. After the warm-up, the athletes carried out a total of six CMJ, which consisted of three jump variants (JV) with two attempts (A) each. A one-minute break was allowed after each attempt. All CMJ were performed with the athletes having their hands on their hips. In this way, the form of the force-time curve was not influenced by the arm swing and analyses focused on the lower-body performance (Lees et al., 2004; Sole et al., 2018). Before each jump variant, the athletes received pre-formulated test instructions which were read out by the experimenter. The different instructions of the three jump variants were: JV1: "Perform a CMJ with the aim of reaching a maximum jump height". JV2: "Perform a CMJ with the fastest possible lowering movement and movement reversal". JV3: "Perform a CMJ with a particularly smooth movement".

2.2 Sample

The two test persons were not selected at random, but they should meet certain criteria. They should have a solid level of athletic ability and familiarity with athletic movements, particularly the CMJ, and should be able to implement movement instructions relatively quickly. Therefore, two physical education students were selected for the study. The study was undertaken with the understanding of the athletes and was conform with the Declaration of Helsinki. Athlete 1 (male, 1.72 m, 74 kg, 24 years) had a lot of previous experience in athletic jumping, athlete 2 (male, 1.80 m, 65 kg, 27 years) was a soccer player with no particular previous experience in jumping. The athletes were not allowed to exercise for 48 hours before the experiment.

2.3 Materials

The jumps were performed indoors on a piezoelectric force plate (Type 9286A, Kistler, Switzerland), which measures and records the ground reaction forces in three dimensions using Bioware® software (Version 5.1.1). A capture frequency of 240 Hz was used. A motion capture suit (XSENS MVN Link, Netherlands) was worn by the test subjects to measure the biokinematic characteristics. The measuring frequency was also 240 Hz. Data were recorded and processed by the associated software. In order to be able to interpret possible ambiguities in the curves, all jumps were also filmed in slow motion using a smartphone. However, these recordings have not been needed.

In order to be able to interpret the force platform data using the motion analysis, both data sets were synchronized for each jump. In the force-time curve, the take-off (t_4) can be determined very reliably when the ground reaction force comes to zero for the first time, i.e. when the jumper leaves the ground. This is the instant, at which the acceleration of the COM in the graph of the angular acceleration corresponds to the gravitational acceleration which can also be determined very reliably. The curves were therefore superimposed in such a way that t_4 was in the same frame for both datasets.

2.4 Variables

The following further time events were determined from the curves produced: the onset of the movement (t_0), the highest downward acceleration (t_1), the bottom of the countermovement (t_2), the highest upward acceleration (t_3), the highest point of the COM (t_5), and the landing (t_6). The duration of the countermovement was calculated from t_0 to t_2. The contraction time t_c extends from the onset of the movement t_0 to the take-off t_4. During the whole movement phase, the athlete's vertical velocity as well as the height of the COM was determined according to Wank (2021). The maximum height of the COM above the standing height was regarded as the jump height. For the countermovement depth, the lowest point of the COM between t_0 and t_2 was taken.

The peak force F_{peak} during the jump was determined from the force-time curve. If the curve had two force peaks, the minimum between the peaks F_{min} was determined, and the height of the dent F_d was calculated as the difference of F_{peak} and F_{min}. The braking end force F_{bef} corresponds to the force exerted at the end of the countermovement at t_2. The impulses P_1 (unweighting), P_2 (braking), P_3 and P_4 (propulsion) were calculated using integrals, described by the mean value of the respective upper and lower sums. The efficiency of the stretch-shortening cycle was calculated as the ratio of the negative impulse to the positive impulse (NPI) (Dowling & Vamos, 1993).

The course of the joint angles was obtained from the XSens measurement. The degrees of angles were given according to the neutral-zero method. 0° corresponds to the neutral position, i.e. a person standing upright. The mean values of the right and left joints were used to display the angle curves, and the graphs were smoothed with a moving average over 10 frames.

3 Results

3.1 Force-time curves

In the force-time curves, differences between the two athletes and the three jump variants could be seen. In both athletes, two-peaked curves occurred in JV1 and JV3, whereby the first force peak was always higher than the second. In contrast, the jumps in JV2 only had one force peak in both athletes. Athlete 1 showed only slightly distinct two-peaked curves in JV1 and JV3, whereas athlete 2 showed two more distinct force peaks. In general, the first force peak coincided with the time of the reversal of the movement to within a few hundredths of a second.

Table 1 shows the descriptive data for each jump of the two athletes. On average for both attempts, athlete 1 achieved the highest jump heights in JV3, the values of JV1 and 2 were slightly lower. For athlete 2, the greatest jump heights were reached in JV1, slightly lower in JV2, and again lower in JV3. Overall, the jump heights in athlete 1 were a bit higher than in athlete 2 and differed only slightly, whereas athlete 2 had a somewhat larger range.

Tab. 1. Kinematic and dynamic characteristics of the jumps of the two athletes in the different jump variants.

		Jump Variant 1 (maximum height)		Jump Variant 2 (rapid countermovement)		Jump Variant 3 (smooth motion)	
	Athlete	Attempt 1	Attempt 2	Attempt 1	Attempt 2	Attempt 1	Attempt 2
Jump Height [cm]	1	33.3	35.0	33.8	34.9	35.5	36.0
	2	33.5	34.7	33.5	33.5	32.2	30.9
Peak Force [N]	1	1750.2	1779.1	2152.5	2056.7	1743.7	1835.3
	2	1473.9	1525.9	1627.0	1616.5	1310.2	1357.2
Braking End Force [N]	1	1703.7	1775.1	2123.5	2046.8	1739.4	1835.3
	2	1470.7	1525.9	1627.0	1603.8	1291.1	1342.9
Dent Height [N]	1	185.2	268.2	-	-	232.9	367.6
	2	271.8	339.4	-	-	133.5	168.1
NPI [%]	1	0.49	0.50	0.57	0.58	0.48	0.53
	2	0.45	0.46	0.53	0.55	0.45	0.42
Contraction Time [s]	1	0.81	0.83	0.63	0.70	0.85	0.85
	2	0.88	0.83	0.71	0.70	0.92	0.90
Countermovement Depth [cm]	1	27.5	27.7	24.1	25.8	28.3	29.6
	2	31.3	31.1	25.4	26.9	29.1	30.5
Duration of the Countermovement [s]	1	0.54	0.55	0.40	0.45	0.57	0.56
	2	0.58	0.53	0.45	0.43	0.61	0.60

In the jump variant with the demanded rapid countermovement (JV2), both athletes produced their greatest peak forces. Also, the braking end forces were substantially higher than in the other two JVs resulting in the highest NPI ratio. Further, the duration of the countermovement as well as of the overall contraction was shortest, with the knees and hips being bent the least in this jump variant. In contrast to this, the contraction time was longest for both athletes in their smooth jumps (JV3).

3.2 Motion analysis

For the motion analysis, the jump with the greatest dent height and the smoothest jump were selected. These were the second attempt of jump variant 1 of athlete 2, and the second attempt of jump variant 2 of athlete 1. The force-time curves and the angular velocities of the hip, knee, and ankle joints for these two jumps are shown in the upper and lower diagrams in Figure 1, respectively. The plot is chosen so that the curves end on the right with the take-off at $t_4 = 0$. In the upper diagram, where jumping should be as high as possible without any further instructions, one can see two pronounced peaks in the force-time curve. At the onset of the movement when going low, the hip and knee joints were flexed simultaneously. The ankle joint also began to flex, but at a lower angular velocity.

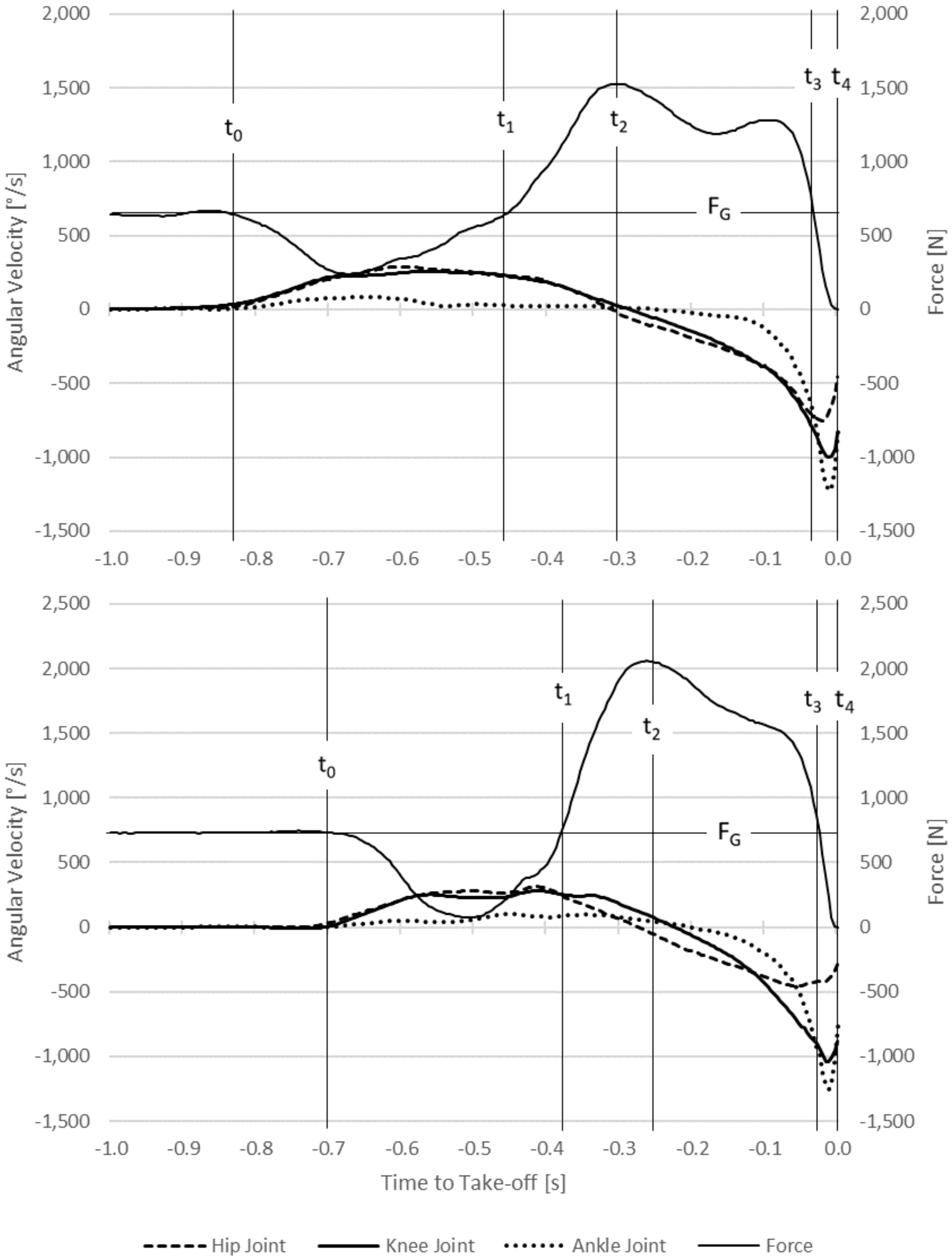

Fig. 1. Force-time curves and angular velocities of the hip, knee, and ankle joint of the second attempt of jump variant 1 (maximum height) of athlete 2 (upper diagram), and of the second attempt of jump variant 2 (rapid countermovement) of athlete 1 (lower diagram)

From t_1, the downward movement slowed down. The curves show that the bending velocity in the hip and knee decreased, and the ankle joint was already in maximum flexion. At t_2, the movement reversed, and the angular velocities were all zero. In this attempt, this moment coincided with the first force peak. This does not have to be the case, but the peak force in this type of jump is very often close to the reversal of the movement (McMahon et al., 2018). From t_2, the athlete began the upward movement. Hip and knee began to extend at almost the same time and at a very similar speed. The angular velocity then increased sharply from approximately 0.1 s before the take-off. At the same time, the extension of the ankle joint began, which occurred immediately at high speed. The second peak in the force-time curve occurred at precisely this point. Shortly before leaving the plate, the angular velocities decreased again, as the joints were now almost fully extended. The pattern was very similar for all of this athlete's jumps in which a two-peaked curve occurred. In the other athlete, the movement of the hips began somewhat earlier, but the basic pattern here was also similar to the jump just described.

In the jump shown in the lower diagram, the instruction was to go down as quickly as possible and to realize a rapid reversal of movement. Initially, no major difference can be seen in the course of the angular velocities. However, the athlete broke the hip flexion more quickly so that he had already started to extend his hips at the moment of the reversal of movement. Due to the rapid lowering movement, the first peak force was slightly before t_2. In contrast to the jump in the upper diagram, a relatively even acceleration can be seen in the knee and hip from t_1 to t_3. There was no extreme acceleration in either the knee or the hip shortly before the take-off. On the contrary, the angular velocity of the hip joint already stagnated before t_3. Compared to JV1, the ankle joint began to extend slightly earlier, but was then accelerated very strongly towards the end, very similar to the other jump. However, this additional impulse shortly before the take-off did not lead to a second force peak.

Consideration of the angular velocities suggests that the height of the second peak is primarily due to two phenomena:

1) the additional impulse due to the extension of the ankle joint

2) the increased acceleration of the hip and knee joint in the movement phase shortly before the take-off.

4 Discussion

The various instructions generated different jumps in terms of jump height, jump duration, countermovement depth, force peaks, generated force-time curves, and the course of the angular velocities of the hip, knee, and ankle joints. In accordance with the literature, the shorter and faster countermovement in jump variant 2 led to a shorter jump duration (Kennedy & Drake, 2018) and higher force peaks, but not to a greater jump height (Gheller et al., 2015; Pérez-Castilla et al., 2021; Salles et al., 2011). Dowling and Vamos (1993) had already shown that the generation of a high peak force is less relevant for the jump height than the pattern of force application. In our study, the generated force-time curve for this variant had a single peak as in Pérez-Castilla et al. (2021) for all conducted attempts. One might think that single-peaked curves are due to better intersegmental coordination and due to an efficient stretch-shortening cycle (Kennedy & Drake, 2018), which should theoretically lead to better jumping performance. However, a couple of studies have shown that greater jump heights were generated with double peak curves (McMaster, 2016; Peng et al., 2019). In our study, this also applies to athlete 1. Athlete 2 achieved the greatest jump heights in jump variant 1 with two-peaked curves, almost the same heights in jump variant 2 with one-peaked curves, and his lowest jump heights in jump variant 3 with two-peaked curves. The instruction to produce a smooth movement in JV3 therefore neither led to a single-peaked curve nor to a better jump height. The fact that within the same person the pattern is not consistently one- or two-peaked for every jump is also in line with the study by Lake and McMahon (2018), in which 40% of the subjects showed an inconsistent pattern across ten jumps.

Although much research has been conducted on whether single or double peaks in the force-time curve are more effective in the concentric phase in CMJs, there have been few studies that have attempted to elucidate how they occur. Using kinematic analyses, Peng et al. (2019) found that hip, knee and ankle flexion and hip and knee moments were greater in jumps with double peak curves. They stated a better proximal to distal timing of extensor concentric contractions sequence of the lower extremities. However, the course of the angular velocities had not yet been fully resolved. In our study, we were able to show that the double peak is caused by additional impulses in the movement phase shortly before take-off, that do not occur in single peaks. This is mainly due to the increased acceleration of the hip joint shortly before the take-off. This further accelerates the COM, which results in a higher take-off velocity and thus a higher jump height. In single peak curves during the fast reversal movement, the hip extension already occurred earlier in the reversal phase and was therefore no longer increased at the end of the take-off movement. The additional acceleration through the ankle joint occurred in both curve patterns. It contributes to a brief slowing of the steep drop of the curve until the take-off in single peak curves. In the double peak curves, it slightly intensifies the second peak.

The results of this study may make a small contribution to making the occurrence of double peaks in the force-time curve of CMJs comprehensible. They may also help to partially explain the sometimes-inconsistent findings of other studies. The distinction between one- and two-peaked curves is biomechanically clear. However, the classification into one or the other pattern is sometimes decided by only a few Newtons, so that it may be better to speak of characteristics on a continuum than of two completely different movement sequences. The significance of the generating one or the other curve pattern may therefore be somewhat over-interpreted. Small changes in the execution of the movement – whether due to different instructions as in our experiment or due to the normal fluctuation when performing the same movement task several times – can therefore lead to the generated curve having either one peak or two peaks. This explains, for example, the inconsistent patterns in several jumps in the study by Lake and McMahon (2018).

Good intersegmental coordination theoretically leads to improved jumping performance. However, this is not expressed in the fact that only one peak is generated by the fast reversal movement, but in the fact that the COM velocity is greatest at the end of the take-off movement. Many jumpers achieve this through the impulse boost shortly before take-off, which results in a second peak and therefore appears to be a good strategy for achieving a high jump height (McMaster, 2016; Peng et al., 2019).

Limitations

An obvious limitation of our study is the small number of twelve analyzed jumps of two different jumpers. This means that the general applicability must be viewed critically. Newer technologies for capturing angular velocities will certainly help to ensure that such studies can be replicated with reasonable effort and will therefore have a greater impact. It was also not possible to represent all possible types of counter movement jumps in our study. It must be assumed that elite athletes from different disciplines also show different jump characteristics.

In our study, the athletes were asked to implement the given instructions for different jump variants directly the first time they performed the movement. As they were experienced athletes, this was achieved quite well, as can be seen from the curves generated. Nevertheless, it would certainly also be interesting to examine longitudinally whether the athletes can also achieve a long-term improvement by training a different type of execution. Interestingly, athlete 1 achieved his best jumping performance with the instruction to generate a smooth movement sequence, even better than with his self-chosen form of execution.

As mentioned above, the CMJ is a very important diagnostic tool in many sports. Many authors see potential in it, but also a need for further research (Brady et al., 2017; McMahon et al., 2018; Sole et al., 2018). Despite its limitations, this study may therefore have a relevant impact for researchers and for coaches in the field of jump optimization.

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