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High-speed x-ray video demonstrates significant skin movement errors with standard optical kinematics during rat locomotion

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Abstract

The sophistication of current rodent injury and disease models outpaces that of the most commonly used behavioral assays. The first objective of this study was to measure rat locomotion using high-speed x-ray video to establish an accurate baseline for rat hindlimb kinematics. The second objective was to quantify the kinematics errors due to skin movement artefacts by simultaneously recording and comparing hindlimb kinematics derived from skin markers and from direct visualization of skeletal landmarks. Joint angle calculations from skin-derived kinematics yielded errors as high as 39° in the knee and 31° in the hip around paw contact with respect to the x-ray data. Triangulation of knee position from the ankle and hip skin markers provided closer, albeit still inaccurate, approximations of bone-derived, x-ray kinematics. We found that soft tissue movement errors are the result of multiple factors, the most impressive of which is overall limb posture. Treadmill speed had surprisingly little effect on kinematics errors. These findings illustrate the significance and context of skin movement error in rodent kinematics.

Keywords

rodent; walking; biomechanics; assay; joint angle; gait analysis

1. Introduction

Rats and mice constitute the overwhelming choice for animal research models in the United States constituting approximately 98% of all animals used for biomedical research (Anon., 2001). With the wide range of disease models developed for biomedical research as well as the continued rise of genomic methods, the rat will likely continue to be relied upon as a model organism for studying the rehabilitation of central and peripheral nervous system after injury. Yet, it is questionable whether the accuracy of the joint kinematics methodologies currently available is sufficient to evaluate future injury and disease models. The detection of behavioral differences resulting from the subtle changes in motor output that often accompany different injury models demands more accurate and comprehensive measurement techniques.

Two widely used methodologies for quantifying rat locomotor behavior are the Sciatic Function Index (Bain et al., 1989) and the BBB locomotor rating scale (Basso et al., 1995), designed to evaluate recovery following sciatic nerve and spinal cord injuries, respectively.

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Although these continue to be excellent measures for gross behavior differences, Metz and colleagues have recommended supplemental assays as they found small but important behavioral changes between sham and pyramidal tract lesion rodents, yet equal BBB scores (Metz et al., 1998; Metz et al., 2000). Other investigators have also recommended more quantitative tests to analyze gaits among which more qualitative tests could not discriminate (Ballermann et al., 2006). For example, Varejao et al. (Varejao et al., 2003; Varejao et al., 2001) observed gait deficits in ankle kinematics after peripheral nerve injury despite SFI results indicating a full recovery. Even with ankle kinematics alone, no inferences can be drawn regarding the neuromuscular function of the majority of the limb muscles that cross the more proximal limb joints or any effects on intralimb compensation and coordination.

The major impediment to the adoption of whole limb kinematics in rats is the inaccuracy of joint kinematics measurements due to skin movement errors. Already acknowledged to be an important source of error in human kinematics (Alexander and Andriacchi, 2001; Capozzo et al., 1996), the much looser soft tissue of the rat hindlimb moves even more freely relative to the underlying limb bones, resulting in a significant magnitude of error in the proximal limb joints (Muir and Webb, 2000). Previous whole limb kinematic analyses in the rat have either neglected to account for skin error, or utilized a triangulation algorithm that assumes an improved estimate of knee joint position (Filipe et al., 2006). For the field to continue to advance, however, the obstacle of skin movement error must be overcome.

In this study, we simultaneously and directly compared three different methods for obtaining high-speed joint kinematics data during treadmill locomotion in rats: direct skeletal tracking (bone-derived kinematics); tracking of markers placed on the skin (skin-derived kinematics); and skin-derived kinematics with a calculated estimate of knee position (triangulated kinematics). Direct visualization of the appendicular skeleton during locomotion provided the best possible estimate of hindlimb joint centers without any influence from skin movement artefacts. Any differences from the bone-derived kinematics in the simultaneously measured skin-derived and triangulated kinematics methods would then provide the errors due to skin and soft tissue movement.

Our primary goal was to accurately quantify the hindlimb joint angular excursions of healthy, intact rat locomotion across several locomotor speeds using high-speed x-ray video. Secondly, we compared these bone-derived, x-ray kinematics to those derived from the two most commonly used skin marker kinematics methods and mapped the conditions in which skin movement error was mitigated. We hypothesized that the magnitude of joint angle error due to skin movement would be greatest in the knee and hip compared to the ankle. We further correlated these errors over a range of speeds and across the entire gait cycle to examine the influences of dynamic limb movements and static limb posture, respectively. We hypothesized that the magnitude of skin movement error in each joint would increase with respect to greater treadmill speeds and with more extreme limb orientations.

2. Materials and Methods

Using high-speed x-ray video analysis, we simultaneously recorded bone-derived and skin-derived positions of anatomical landmarks from the same stride cycles to quantify errors that were due only to skin movement. We also triangulated the knee joint center from the skin markers as an additional third kinematics method. This experimental design inherently eliminated any inter-trial variability such that all differences in joint angle measurements were due solely to differences between the three tested kinematics methods, which we refer to as: (i) bone-derived; (ii) skin-derived; and (iii) triangulated.

2.1 Animal care and training

We tested six adult male Sprague-Dawley rats (average weight 250.74 ± 33.30 g) in accordance with a protocol approved by the Georgia Institute of Technology IACUC. Each animal was prepared for experimental trials by shaving the fur from the left hindquarters and hindlimb while under isoflurane gas anesthesia (5% induction, 2–3% maintenance). The rats were held in a prone position, supported beneath the torso with the hindlimbs positioned on the floor below the body such that the MTP joint was vertically aligned with the hip joint. Care was taken to maintain the rats in this posture, which approximated a mid-stance limb posture during locomotion to make the best possible correspondence between skin-derived and bone-derived markers. Six anatomical hindlimb features were marked with permanent ink after careful identification through manual palpation: the 4th distal phalanx, 4th metatarsal head, lateral malleolus of the fibula, lateral epicondyle of the femur, greater trochanter, and the caudal margin of the ischium (Fig. 1). After the positions were verified and corrected as necessary, 0.8 or 1.0 mm radio-opaque tantalum spheres (RSA Biomedical) were glued to the marked skin with cyanoacrylate gel.

2.2 Data collection

During experiments the animals were enclosed in a $21.5 \times 15.0 \times 56.0$ cm Plexiglas treadmill (Rat Modular Treadmill, Columbia Instruments) oriented perpendicular to the beam of a custom-built high-speed x-ray video system (Fig. 2). X-rays were emitted by a continuous beam x-ray emitting tube (97 kV, 2 mA, Monoblock-160, VJ Technologies). The photons passed through the animal and into a 225 mm diameter input window image intensifier (TH-9438-HX, VJ Technologies) where they were converted to visible light (548 nm wavelength) and recorded by a high-speed digital video camera (A504k, Basler Vision Technologies). All data were recorded at 200 Hz and saved using commercial software (Streampix, Norpix, Inc.) to a dedicated computer. We constructed a 2-D calibration frame consisting of lead beads ordered in a square grid pattern (1 cm apart) on a plexiglass sheet to autocorrect for any image distortion that may have occurred. A CNC mill was used to mark the placement of the lead beads to ensure accuracy of bead placement to within 0.00254 mm. Commercial image correction software (NI Vision software, National Instruments) was used to correct video data against the calibration grid.

Each rat was acclimated to the treadmill at a sampling of different speeds one week prior to the first experimental trial. A single data collection trial consisted of a ten second x-ray exposure while the rat locomoted steadily at a constant speed. An entire day's session was composed of 10–12 trials over a range of treadmill speeds (16.5–63.2 cm/s), which were adjusted to the animal's capabilities for that day. Each rat participated in three data collection sessions over the course of approximately 14 days.

2.3 Data processing

After data collection, we visually assessed videos for steady locomotion and cropped them into shorter clips containing at least three consecutive strides. Data clips contained 8.94 ± 7.70 strides with a range of 3–30 strides across all animals. We defined a stride as one ipsilateral paw contact to the successive ipsilateral paw contact. We then exported the clips as sets of still images for the purposes of x-ray image auto distortion correction and contrast enhancement, which were accomplished using commercial image analysis software (NI Vision software, National Instruments). We then reconstituted the individual images back into a video file for digitization. We separately image enhanced and digitized each clip depending upon the different tracking targets. In this way we maximized contrast and identification of skeletal landmarks for the bone-derived kinematics and the tantalum markers for the skin-derived kinematics. The radio opaque tantalum spheres demonstrated sufficient contrast to be automatically tracked with an open source Matlab software (Hedrick, 2008). The bony

landmarks were manually digitized through frame-by-frame inspection and identification with visual reference to an articulated rat skeleton.

In addition to direct digitization of the knee position via the attached skin marker (i.e., skin-derived kinematics), we also estimated knee position through triangulation (i.e., triangulated kinematics), another common optical kinematics technique (Chang et al., In press; Chang et al., 2008). The inputs for the triangulation method included the sagittal plane skin-derived positions of the hip (greater trochanter) and ankle (lateral malleolus) as well as the averaged femur and shank lengths (measured from x-ray video data). We then triangulated the position of the knee joint center by finding the two points of intersection between two circles with centers defined by the ankle and hip joint markers and radii defined by the length of the respective femoral and tibial limb segments, of which only one solution is anatomically viable. Note that the results of the triangulation method share with the skin-derived measurements the positions of all joint centers except the knee, however, a difference in knee position will affect the calculation of all three joint angles.

We transformed the three sets of estimated joint position data into corresponding sets of sagittal plane included joint angles using custom Matlab code (Fig. 1). Hip angle was defined by the supplement of the angle formed by the knee joint center, greater trochanter, and caudal point on the ischium. Knee and ankle joint angles were defined by the smaller angle formed by the joint in question and the adjacent proximal and distal joint positions. We time-normalized all step cycles to one hundred percent of the stride cycle beginning with paw contact on the ground.

We performed a student's t-test ($\alpha=0.01$) on the mean kinematics trajectory data at every 1% of the gait cycle to test for statistical differences of the bone-derived kinematics data against: (i) the skin-derived kinematics; and, (ii) the triangulated kinematics. All t-tests and regression analyses were performed with MATLAB software.

3. Results

For each animal, we pooled all step cycles from all trials at a given speed to generate a single representative mean trajectory for that animal and condition. We then calculated mean kinematics trajectories for each of 12 treadmill speeds across all animals, as well as for all cycles ($n=237$) from all speeds pooled together.

3.1 Locomotor Kinematics

Stick figure reconstructions of the hindlimb kinematics data show clear qualitative differences in the limb configurations estimated by the three kinematics methodologies at key times during the stride (Fig. 3). All joint positions calculated with skin-derived or triangulated methods indicated some differences to the bone-derived kinematics. Estimates of knee position were particularly poor compared to hip and ankle. We observed particularly striking differences in the estimated knee positions at the instant of paw contact.

Skin-derived knee and hip joint kinematics differed significantly from bone-derived kinematics ($p < 0.10$) for at least 50% of the gait cycle for every speed surveyed (Fig. 4). The largest error between skin and bone-derived angles for all three joints always occurred just before the instant of paw contact. The magnitude of greatest error was $31 \pm 22^\circ$ for the hip ($p < 0.001$), $39 \pm 6^\circ$ for the knee ($p < 0.001$), and $14 \pm 6^\circ$ for the ankle ($p < 0.001$). Skin-derived hip angle values consistently overestimated bone-derived kinematics and also erroneously indicated a greatly reduced hip range of motion across the stride cycle. Skin-derived kinematics overestimated knee angle values and exaggerated knee range of motion, and lacked the inflection point observed with bone-derived kinematics during late stance. Skin-derived ankle kinematics most closely resembled bone-derived kinematics compared to the knee and hip data. Nevertheless,

ankle angle values had significant errors for large portions of the stride cycle over all speeds. Skin-derived ankle kinematics were also generally more accurate than the triangulated ankle joint trajectories, in contrast to results for the knee and hip.

Joint kinematics calculated with the triangulation method were generally more accurate than the skin-derived kinematics (Fig. 4). Although some differences remained, hip joint kinematics calculated with a triangulated knee position more closely matched the absolute joint angle values and ranges of motion calculated from bone-derived kinematics. Triangulated knee joint angle also more accurately matched bone-derived data, however, peak errors of $17 \pm 11^\circ$ near paw contact persisted ($p < 0.001$). Ankle joint kinematics were actually worse with the triangulation method compared to the skin-derived method with values consistently overestimating ankle joint angle.

3.2 Optical Kinematics Errors due to Movement and Limb Posture

Joint kinematics error (calculated as the difference from bone-derived values) decreased slightly with increasing treadmill speed. The correlation of knee joint angle at paw contact with locomotor speed was greater in skin-derived kinematics ($R^2=0.71$) compared to triangulated kinematics ($R^2=0.35$, Fig. 5A). Hip joint kinematics showed very little correlation with speed for both skin-derived ($R^2=0.19$) and triangulation methods ($R^2=0.15$, Fig. 5B).

We further investigated the errors in estimated joint position from the skin-derived and triangulation methods (Fig. 6). Knee joint positions calculated by both methods had the least amount of error when the hindlimb was most retracted, or the posture adopted near the end of stance phase when the toe is coming off of the ground. We saw the greatest knee position errors for both methods occurring when the limb was most protracted, near the beginning of stance phase when the paw first contacts the ground. Although the skin-derived method had greater errors than the triangulated kinematics, they both showed similar trends with limb orientation angle.

Comparing the joint center accelerations calculated by bone-derived and skin-derived kinematics provided insights into the dynamic effects of the inertial properties of the skin and soft tissue during locomotion. We calculated the second-derivative of the resultant (RMS) position to obtain a single metric of sagittal plane joint center acceleration for the knee and hip joints (Fig. 7), which are the joints with the most soft tissue movement. The skin-derived method overestimated peak joint center acceleration and deceleration for both joints compared to bone-derived joint accelerations. The skin-derived knee acceleration trajectory also displayed an important divergence from the bone-derived data in late stance phase. Bone-derived knee joint acceleration had a bimodal trajectory, whereas the skin-derived trajectory had a unimodal trajectory (Fig. 7A). Peak joint accelerations decreased with increasing treadmill speed for both the knee and hip joints (Fig. 8). The estimated peak joint accelerations from the skin-derived data were always greater than those from bone-derived kinematics. These differences decreased with speed for peak knee joint acceleration, whereas the difference in peak hip acceleration remained constant across all speeds. These joint position errors due to soft tissue movement and kinematics methodology resulted in substantial effects on a common measure for characterizing interjoint coordination: angle-angle plots. The knee-ankle coordination estimated by both skin-derived and triangulated kinematics methods grossly misrepresented the ranges of movements of both joints as well as the characteristic shape of the interjoint coordination pattern compared to calculation from actual skeletal movements (Fig. 9).

4. Discussion

The main goal of this study was to quantify and compare the joint kinematics calculated over a range of locomotor speeds using three different methodologies. Since our experimental design ruled out inter-trial variability by using the exact same step cycles to compare each method, any differences can be attributed to errors due to skin and soft tissue movement. As those differences were often significant, we made a primary assumption that kinematics from bone-derived joint positions were the most accurate of the three due to the direct identification of joint centers from skeletal landmarks, which bypassed influences from all soft tissues (Fischer et al., 2002). The inter-cycle variability for the bone-derived kinematics was consistent with the other two methods (average $SD=4-7^\circ$ for all three methods), suggesting that the digitizing process was consistent across strides for all three methods.

While detailed rat hindlimb kinematics have been limited to only a handful of studies, our results are consistent with respect to previous findings for each of the three respective methodologies. Our skin-derived joint angle trajectories are consistent with previously published results of rat hip (Filipe et al., 2006; Pereira et al., 2006) and knee (Filipe et al., 2006; Gillis and Biewener, 2001; Pereira et al., 2006; Thota et al., 2005) kinematics. Our triangulated knee joint angles were also similar to previously published knee kinematics using the triangulation method (Filipe et al., 2006). Kinematics from all three joints of our bone-derived kinematics agrees to within 10° of the only other limited description of x-ray kinematics in a common laboratory rat (*R. norvegicus*, (Fischer et al., 2002)), which showed data from only one cycle from one animal. The magnitudes of our ankle angles were slightly smaller for the skin-derived and triangulation methodologies throughout the stride cycle than those in the published literature (Filipe et al., 2006). This is most likely due to a more cranially estimated knee position in our skin-derived and triangulated data, which in our study actually better matched the bone-derived measurements.

With respect to skin-derived kinematics, we accept our first hypothesis that the magnitudes of joint angle errors due to skin-derived kinematics are greater in the proximal knee and hip joints compared to the more distal ankle joint. The skin-derived hip and knee joint angles were significantly different from those of bone-derived marker positions for much of the gait cycle across all speeds. The magnitude of this error, particularly that of the knee joint at paw contact, confirms the general hypothesis that skin-derived kinematics can be exceedingly inaccurate. In addition, the amount of joint kinematics error changes over the stride cycle, with treadmill speed and general limb posture such that a simple systematic baseline correction is not of any use. Therefore, any use of skin-derived joint kinematics in rats (and presumably mice and other small mammals) should be done with great caution since the knee and hip angles could be overestimated by up as much as 39° and 31° , respectively.

By comparison, the triangulated knee and hip joint trajectories are more accurate over much of the stride cycle, often staying within one standard deviation of the mean bone-derived kinematics. The error measured in ankle joint angle produced by a triangulated knee position, however, is often larger than the errors in knee and hip across all speeds. Therefore, we reject our first hypothesis for triangulated kinematics.

Our secondary goal was to analyze potential sources of the skin movement errors. We considered both inertial (dynamic) and postural (static) components to skin movement error. Our second hypothesis predicted that joint kinematics errors would increase with treadmill speed and also with more extreme ranges of limb posture. This was partially predicated on the notion that greater limb segment velocities generated during faster locomotion would increase inertial movements of the skin, and thereby increase the error between skin and bone-derived kinematics. Surprisingly, we found that the opposite occurred. There was a slight decrease in

joint kinematics errors with locomotion at greater treadmill speeds. Both skin-derived and bone-derived peak joint accelerations unexpectedly decreased with speed, so we reject our second hypothesis with respect to the increased errors due to inertial effects at faster speeds. It is worth noting that the greater peaks and the difference in trajectory shapes of the skin-derived and bone-derived accelerations support the notion that the dynamics of soft tissue movements are different from those of the skeleton (Fig 8).

Limb posture may be the single greatest determinant to explaining the accuracy of skin-derived kinematics. The errors in knee joint center positions reached a minimum at the most protracted leg angle for both skin-derived and triangulated methods. This protracted limb posture corresponds to the end of the stance phase, where the minimum joint angle differences can be seen to occur. This also corresponds to the most extended postures for each individual joint, which likely helps to minimize the effects of any errors in joint center positions. Conversely, maximum errors for both skin and triangulation-derived knee positions occurred just before paw contact, which also corresponds with each of the joints being in generally flexed postures. This relationship generally holds at the postural extremes of the limb orientation, but the hysteresis shown in Fig. 6 implies that other unknown variables are needed to fully explain the nonlinear pattern of joint angle errors across the stride cycle. Nevertheless, there is a good correlation of knee error with the toe-to-hip limb orientation for both kinematics methods.

Skin movement error is particularly exacerbated at early stance, mitigated in late stance, and may be slightly attenuated at higher walking speeds. Our observation that errors are minimized around toe off corresponds with some recommendations in the literature for the gait events at which sciatic and peripheral nerve injuries should be evaluated (Lin et al., 1996; Yu et al., 2001). Again, however, this advice should be taken with some trepidation since there is currently no standardized method for selecting the limb posture at which skin markers should be attached. This practically precludes the recommendation of a strict skin movement error correction algorithm, as the trajectories of the errors may depend on the initial marker placement. Correspondingly, an interesting area for further investigation would be to study the effects of changing the limb posture at which skin markers are attached to see if it is possible to target specific portions of the gait cycle where accurate kinematics can be consistently attained.

Accurate kinematics are a prerequisite for higher-level neuromechanical analyses such as those requiring the characterization of interjoint coordination patterns or the calculation of joint torques generated during locomotion. We have shown, for example, that the interjoint coordination pattern between the knee and ankle joints can appear to be quite different depending solely on the kinematics method used (Fig. 9). Quantification of interjoint coordination can be an important tool for characterizing subtle changes in locomotor control during recovery from nerve injury. As we show, the errors associated with non-bone-derived kinematics can lead to very misleading conclusions about how the joints are being controlled and coordinated during locomotion. The bone-derived kinematics associated with x-ray videography currently yields the most accurate kinematics measurements in rodents. Fortunately, this is a technology that is becoming increasingly common and accessible to researchers in a growing number of fields from comparative biomechanics (de Groot et al., 2004; Druzisky and Brainerd, 2001; Fischer et al., 2002; Jenkins, 1972; Jenkins, 1970; Jenkins et al., 1988a,b; Snelderwaard et al., 2002), orthopedic biomechanics (Banks et al., 2005; Fregly et al., 2005; Tashman and Anderst, 2003; You et al., 2001), and neuroscience (Boczek-Funcke et al., 1994; Boczek-Funcke et al., 1999; Boczek-Funcke et al., 2000; Graf et al., 1995; Kuhtz-Buschbeck et al., 1996; Rabbath et al., 2001; Vidal et al., 2004). To our knowledge, this is the first systematic use of high-speed fluoroscopy to quantify limb movements in standard laboratory rats.

There are some drawbacks to the choice of x-ray fluoroscopy. Like other biomechanics methodologies, data analysis may demand a large amount of manual digitization with some opportunity for automatic tracking. Our x-ray fluoroscopy system provides better accuracy of sagittal plane kinematics for rat locomotion compared to traditional optical video systems, but there are currently several 3-D x-ray kinematics systems in use in the field that could potentially provide more comprehensive information. A wider range of hypotheses involving pathological rodent gait models could be tested with joint kinematics from three planes. Our system provides accurate sagittal plane kinematics, however, a biplanar x-ray system may be useful to describe anatomical flexion-extension angles in 3-D space if significant out-of-plane motion is suspected. State-of-the-art biplanar fluoroscopy systems already in use permit measurement of 3-D kinematics as well as automatic bone tracking based on CT measurements (Dawson et al. 2009, Fahrig et al. 1997; Keefe et al. 2008; Li et al. 2006; Tashman and Anderst, 2003; Tashman et al. 2004; You et al. 2001). Furthermore, existing techniques also provide the opportunity for best-fitting accurate 3-D skeletal models derived from CT scans onto 2-D x-ray images (Banks et al., 2005; Fischer et al. 2001; Fregly et al. 2005).

We have demonstrated joint kinematics measured directly from the underlying skeleton during locomotion in a group of normal healthy rats using high-speed x-ray fluoroscopy. We also provide a systematic quantification of the likely errors that would be calculated at different locomotor speeds from typical optical kinematics techniques using skin-derived and triangulated kinematics methods. We determined that errors are large in the knee and hip joint when kinematics are calculated using skin-derived methods, and in the ankle when knee triangulation methods are used. We further found that increasing locomotor speed has a slight attenuating effect on some of these errors, but that much of the errors can be attributed to the soft tissue artefacts associated with the general orientation of the limb. Although relatively few investigators currently use high-speed x-ray kinematics for neuroscience research, given the continued importance of rats and mice as research models for human disease these techniques are likely to become a standard wherever high precision or great accuracy is required in a behavioral assay.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

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Figure 1.

Sagittal plane kinematic model of rat hindlimb. Six tantalum markers (filled circles) were placed over bone landmarks corresponding to (proximal to distal): caudal ischium, greater trochanter, lateral epicondyle of the femur, lateral malleolus of the fibula, fourth metatarsal head, and the fourth distal phalanx. Included joint angles for hip, knee, ankle and metatarsophalangeal joints along with limb orientation were calculated.

Figure 2. Schematic of experimental set-up consisting of custom x-ray tube, rat on treadmill, image intensifier, high-speed digital camera, and computer interface.

Figure 3.

Stick figures of the hindlimb showing average joint center positions calculated from bone-derived (gray), skin-derived (solid black) and triangulated (dashed) kinematics methods. Four specific times during the stride cycle are shown for four animals walking at 39.83 cm/s. Data are averaged over 44 gait cycles.

Figure 4.

Mean kinematics for the hip (A), knee (B), and ankle (C) joints calculated from bone-derived (gray ± 1 SD), skin-derived (solid) and triangulated (dashed) kinematics methods for the same representative animals as in Figure 3. Vertical line indicates end of stance phase and beginning of swing phase.

Figure 5.

Knee (A) and hip (B) joint angle error at foot contact as a function of treadmill speed due to skin-derived (solid) and triangulated (dashed) kinematics methods. Joint angle error was defined as the difference with respect to bone-derived kinematics. Each symbol represents the average of all animals tested at that particular speed.

Figure 6.

RMS error in knee joint position estimated from skin-derived (solid) and triangulated (dashed) methods as a function of limb orientation. Mean trajectories are pooled from all six rats across all treadmill speeds. Circles represent paw contact and the beginning of stance phase (thick lines) and end of the swing phase (thin lines). Arrows indicate flow of time over the stride cycle.

Figure 7.

Mean resultant knee (A) and hip (B) joint acceleration trajectories calculated from both skin-derived (black) and bone-derived (gray) methods pooled for all rats across all speeds. Vertical line indicates transition from stance to swing.

Figure 8.

Maximum knee (A) and hip (B) joint acceleration values calculated from both skin-derived (black) and bone-derived (gray) methods as a function of treadmill speed. Each symbol represents the average of all animals tested at that particular speed.

Figure 9.

Mean interjoint coordination patterns of the knee joint angle as a function of ankle joint angle calculated from bone-derived (gray), skin-derived (solid black) and triangulated (dashed) kinematics methods for four animals walking at 39.8 cm/s. Circles represent paw contact. Arrows indicate flow of time over the stride cycle.