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Fetal Kinematics: Basic Outcomes and Translational Outlook

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ABSTRACT: This Viewpoint examines recent developments in the quantitative characterization of fetal movements via kinematical analysis. We contend that fetal kinematics represents a powerful tool to investigate prenatal cognition and the prepostnatal continuity of cognitive development. The potential benefits of increased investigation into the kinematics of fetal movement are manifold, and apply to diverse fields including pediatric medicine and developmental biology.

KEYWORDS: *Fetal movement, Kinematics, Potential diagnostic tool*

The study of fetal movements has long been of interest to both the medical and the scientific community, for its potential to illuminate the neurobehavioral development of the fetus as well as its well-being in utero. The first attempts to study fetal behavior included the observation of movements from the outside of the mother's abdomen as well as the investigation of how premature infants move postnatally. However, it is the introduction of ultrasonography in the mid- to late 1970s that has allowed the honest investigation and clear visualization of fetal behavior. Researchers and clinicians were able to map noninvasively, with high accuracy, and longitudinally over the pregnancy a wide range of fetal movements since early gestational ages (∼7 gestational weeks, GW), revealing that by GW 12 the fetal motor repertoire is coordinated, nonreflexive, and mature. After a peak in fetal motor research between 1980 and 1990, the advent of 4D ultrasonography has reignited the interest in this topic by enabling the imaging of the entire fetus, with the precision required to reliably distinguish fine movements, such as hand actions and facial expressions.[1] As it became evident, throughout gestation the repertoire of fetal activities constantly increases and reveals the blueprint of the structural development of the central nervous system over time.[2]

Neural development starts with neurogenesis and differentiation processes in the early fetal period, with corticospinal axons reaching the cervical spinal beginning approximately at 8−9 GW, when coordinated movements have already appeared. Neural circuitry formation appears during midgestation, as a result of complex molecular orchestration. It is around GW 14−15 that a sharp increase of axosomatic synapses on the motor neurons occurs. Increased complexity in prebirth neural networks is achieved during the late fetal period, when it is believed that functional monosynaptic corticomotoneuronal projections are present (GW 26 and onward). Considering that a few neural structures are able to generate well organized, yet not fine-grained movements (i.e., independent finger movement develops 6−12 months postnatally), early corticospinal innervation seems to allow the maturation of spinal motor centers during a critical period of perinatal development.[2]

The cross-correlation between biological aspects of the nervous system and the behavioral motor manifestations suggest that observing fetal movement patterns in a qualitative and quantitative fashion, much like what is done in developmental neurology with postnatal motor patterns, serves as groundwork for the investigation of the typical and atypical development of the nervous system. Indeed, mapping the brain's anatomical, functional, and behavioral trajectories is crucial for the early identification of altered development.

How can the analysis of fetal movements serve this purpose? At its dawn, it was believed that the qualitative assessment of fetal movements would be more informative than a more quantitative approach. If this may be true for analyses based on the pregnant woman's estimates of daily periods of movement of the fetus, the precise breakdown of complex general movement patterns as well the decomposition of isolated movements (e.g., upper limb movements) in quantifiable spatiotemporal parameters has greatly informed how the motor system is shaped, also prebirth.

In particular, fetal kinematics represents a powerful tool to investigate prenatal cognition and the prepostnatal continuity of cognitive development. As others and ourselves have demonstrated, fetal kinematics reveal the anticipation of goals, evidence that constitutes the behavioral indication of some sort of intentionality to be attributed to the fetus. By investigating the role played by the intrinsic features of a to-be-reached target, Zoia and colleagues were able to reveal differences in the velocity profiles and spatial trajectories based on how delicate the to-be-reached target was.[3] Movements toward the eyes lasted longer than movements to the mouth and both required significantly more time than the movements to the uterine wall, in accordance with the adult-like accuracy-speed trade-off. This is also true for social movements in utero, when a twin's actions toward oneself or the other are assessed. Reaching toward oneself is done more quickly than reaching toward the twin, suggesting that the modulation of actions based on social cues is already possible in utero.[4]

As our recent paper also demonstrates,[5] the analysis of fetal kinematics can provide a template for the identification of highly reliable quantitative markers, which can be correlated with neurological dysfunction and therefore acquire prognostic

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value. This represents a particularly good tool for pathologies that may already develop in utero, but whose postnatal behavioral manifestations emerge later on. It is the case, among others, of autism spectrum disorder (ASD), which is characterized by abnormal social and motor patterns in childhood and adulthood. Would it be possible to hint to a risk factor for ASD by evaluating aspects of fetal kinematics? In line with the idea that the assessment of general movements in high-risk newborns offers a better prognosis for the subsequent neurological development than the classical neurological examination, we contend that this represents one of the endeavors that this technique now allows to explore.

However, before identifying reliable motor markers to be used with diagnostic purposes, some caveats have to be advanced. First, the conditions in which the movements are performed change pre- vs postnatally, requiring extreme care in interpreting prenatal signs as postnatal pathological markers within a different context. Indeed, the release of the intrauterine movement restriction as well as the modified gravity experience and friction of the medium in which the movements occur (amniotic fluid vs air) supports the idea that only partial carryover effects may be evident in the movements from the prenatal to postnatal period.[3] Despite this, similar kinematic patterns for upper limb movements hold true prenatally as well as postnatally, suggesting that, with the adequate adjustments, kinematic observations can be translated across environments. Second, the high brain plasticity that characterizes the early stages of life may importantly modify the behavioral expression of motor patterns over time, with effects that span from reduction to improvement of the function. Also, given the incomplete motor development at birth, it is expected that neurological dysfunction may be expressed more as a general deficit rather than a localized deficit. In both cases, kinematic measurements offer the opportunity to capitalize both on single and patterns of measures which can be tracked over time to describe complex developmental trajectories, and their divergent point from normal development. To this end, it becomes important to define the specific temporal windows in which the motor markers appear and a variety of typical and atypical developmental trajectories, as to accurately classify new cases.

All in all, the precise quantification offered by kinematics on the analysis of fetal movements and the ability to evaluate kinematic variables in patterns, as to grasp the complexity of the phenomenon, opens the doors to a deeper knowledge of fetal behavior over gestation as well as to tailor from very early during development the opportunities for individualized diagnoses of atypical fetal behavior. Thus, we expect that fetal kinematics will be used in the near future among the tools to isolate typical and atypical fetal developmental milestones.

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